TAMPERE UNIVERSITY OF TECHNOLOGY

ANNA HOLM

FUEL MIXTURE EFFECT ON BIOMASS BASED POWER PLANTS OPERATION

Master of Science Thesis

Examiner: Professor Risto Raiko
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ABSTRACT

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This thesis is made to UPM Energy for FUSEC (Future Fuels for Sustainable Energy Conversion) project of Tekes and the aim of this thesis is to increase knowledge and gather information about the properties of critical solid fuels and fuel mixtures, to find out the problems caused by biomass power plants, especially bubbling fluidized bed (BFB) boilers, and to find correlations between fuels and failures. These problems affect the availability of the power plant and maintenance costs, so the thesis also aims to create a procedure tools for continuous benchmarking and managing these problems.

Legal obligations, as well as climate change caused pressures to increase the use of biomass based fuels in combustion plants. Fuels become more difficult and demanding, so finding correlations between fuels and the problems is justified. Knowledge of composition and characteristics of the fuel mixture are an important part of the controlling of the problems of boilers.

The work is divided into theoretical and practical parts. In the theoretical part are introduced characteristics of the fuels and the combustion process, combustion technologies and problems in the combustion process. The sources of the theory have been used in the literature, field studies, as well as the knowledge and experience from power plants and experts. The practical part is divided into two parts. In the first part, the tool has been created, which can be estimated due to the problems of fuels incidence. The second part of has been studied in four different BFB boilers of UPM and fuels used in them. It was the aim to find explanations between used fuels and observed problems with the analysis of the given fuel data.

The result of the analysis showed that the systematic gathering of fuel data played a key role in detecting problems. In order to detect problems, must fractions of fuel, the fuel mixture and mixture ratios know well. The estimation tool of the properties of the fuel mixture and the problems will help with this issue. On the grounds of fuel data from power plants was plotted graphs, which support the data of the characteristics of the fuel fractions. Between of used fuels and the problems, the graphs did not found clear correlations, because the problems are complex and due to many different reasons. The fuel data from the power plants was also partially incomplete and variety, so deep analysis was challenging to make. As further actions, I propose a systematic fuel data collection on a monthly basis, as well as the survey of potential of real-time measurement systems. After better fuel data receiving, can be gone deeply into the correlations between fuels and the failures.

TIIVISTELMÄ

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Tämä diplomityö on tehty UPM Energialle Tekesin FUSEC (Future Fuels for Sustainable Energy Conversion) projektin puitteissa ja tavoitteena on lisätä tietoutta polttoaineiden ominaisuuksista, kerätä tietoa kriittisistä polttoaineista sekä niiden vaikutuksista kerrosleijukattiloiden (BFB) ongelmiin etsimällä korrelaatioita polttoaineiden ja ongelmien välille. Nämä ongelmat heijastuvat suoraan kattiloiden käytettävyyteen ja sitä kautta kustannuksiin. Työn tavoitteena on myös luoda työkaluja ongelmien arviointiin ja hallintaan.

Lakisääteiset velvoitteet sekä ilmastonmuutoksen aiheuttamat paineet kasvattavat biopohjaisten polttoaineiden käyttöä polttolaitoksissa. Polttoaineet muuttuvat vaikeammiksi ja vaativammiksi, joten syy-seuraussuhteiden löytäminen polttoaineiden ja ongelmien välille on perusteltua. Polttoaineseoksen koostumuksen ja ominaisuuksien tunteminen on tärkeä osa kattilaongelmien hallinnassa.

Työ on jaettu teoria- sekä käytännön osaan. Teoriaosassa tutustutaan polttoaineiden ja polttoprosessin ominaisuuksiin, polttotekniikkaan ja poltosta aiheutuviin ongelmiin. Lähteinä teoriaosalle on käytetty kirjallisuutta, alan tutkimuksia sekä yrityksen sisältä saatuja tietoja ja kokemuksia. Käytännön osa jakautuu kahteen osaan. Ensimmäisessä osassa on luotu työkalu, jolla voidaan arvioida polttoaineseoksen aiheuttamia ongelmia. Toisessa osassa on tutkittu yrityksen neljää eri BFB-kattilaa ja niissä käytettyjä polttoaineita. Tarkoituksena oli löytää korrelaatioita käytettyjen polttoaineiden ja havaittujen ongelmien välille analysoinnin avulla.

Analysoinnin tuloksena havaittiin, että polttoainetietojen järjestelmällinen kerääminen on avain asemassa ongelmien havaitsemisessa. Jotta ongelmia voidaan havaita, polttoainejakeet, seos ja seossuhteet täytyy tuntea hyvin. Polttoaineseoksen ominaisuuksien ja niistä aiheutuvien ongelmien arviointityökalu edes auttaa tässä ongelmassa. Laitoksilta saadun polttoainedatan perusteella tehtiin kuvaajia, jotka tukevat tietoja kyseisten polttoainejakeiden ominaisuuksista. Käytettyjen polttoainemäärien ja ongelmien välille ei kuvaajien avulla löytynyt selviä korrelaatioita, sillä ongelmat ovat monitahoisia ja johtuvat monista eri syistä. Laitoksilta saatu polttoainedata oli myös osittain puutteellista, joten syvällisiä analysointeja oli haastava tehdä. Jatkotoimenpiteinä ehdotan järjestelmällistä polttoainedatan keräämistä kuukausittain sekä mahdollisten reaaliaikaisten mittausjärjestelmien kartoittamista. Tarkemman polttoainedatan saamisen jälkeen voidaan syventyä polttoaineiden ja ongelmien välisiin riippuvuuksiin.

PREFACE

This thesis has been written for the UPM Energy in between March and November 2012 for FUSEC (Future Fuels for Sustainable Energy Conversion) project. I would like to thank the Generation team of UPM Energy for opportunity to do this thesis. Thanks for my supervisor M.Sc (Tech.) Pasi Svinhufvud and also M.Sc (Tech.) Antti Raukola for their valuable help and useful advice during my work. Also the energy managers of our power plants have given indispensable knowledge for my thesis. I would like also to thank my examiner Prof. Risto Raiko for his comments and advice.

Finally, I would like to thank my family for all their support throughout during my studies. Special thanks to my dear Henri and also people from the Guild of Mechanical Engineering and other students, which I have had pleasure to meet, for their energy and support during my student time.

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Anna Holm

CONTENTS

TERMS AND THEIR DEFINITIONS

ar	as received
daf	dry ash free
d.b.	dry basis
M	molar mass [g/mol]
n	amount of substance [mol]
Q_{gr}	Gross calorific value, GCV, HHV
Q_{net}	Net calorific value, NCV, LHV
wt%	weight percent
tot	total

EIA	Energy Information Administration
FT	Final temperature
GCV	Gross calorific value
HHV	Higher heating value
HT	Hemisphere temperature
LHV	Lower heating value
MSW	Municipal solid waste
NCV	Net calorific value
RCW	Ramial Chipped Wood
RCF	Recovered Fuel
RDF	Refuse Derived Fuel
REF	REcovered Fuel
RES	Renewable Energy Directive (European Union)
SIT	Initial temperature
SOT	Softening temperature
SRF	Solid Recovered Waste
TTT	Temperature, time and turbulence

1 INTRODUCTION

World energy consumption is constantly increasing because of economic and demographical growth. Energy Information Administration's (EIA) Energy Outlook 2011 [1] estimates that world energy consumption will increase 53 % by 2035. It is estimated that renewable energy will grow rapidly, but still in 2035 80 % of the world's energy consumption will be covered by fossil fuels, especially in developing countries.

According to statistics, about 90 % of the world's primary energy production is based on the variety of fuels for combustion. They will be the most important primary energy source furthermore in the future. However, fossil fuels are reduced reserve affected by the growth combustion of biomass in power plants. The pressure to increase this percentage is still hard because of the European Union's Renewable Energy Directive (RES) [2]. The goal is to increase the share of renewable energy to 20 % of final energy consumption by 2020.

Greenhouse gas emissions, especially carbon dioxide emissions from international reduction targets have increased also the interest in to growth the use of biomass and recovered fuels. Biomass does not increase the amount of carbon dioxide in the atmosphere in the long term, as biomass grow, the absorb carbon dioxide the same amount as they released in combustion. Therefore, they count the carbon dioxide-free fuels. Besides the high efficiency and reliability of the power plant, one of the main aims of the modern internal combustion power plant is a minimization of emissions as the lowest cost as possible.

The use of biomass for energy production, in turn, adds the technical requirements in power plants. Biomass and recovered fuels have many properties which have a negative effect on combustion process. The fluidized bed boilers are advanced technology to combustion this kind of fuels. The biggest problems in the combustion of demanding fuels are high temperature chlorine corrosion, slagging and fouling in heat delivery surfaces, erosion, bed sintering, the hardening of bed and generated emissions.

Suggestive estimation for stability of problems can be given for example with key figures and results from previous studies, but this field has many unsolved problems. New problems with new fuels are coming so researching for this field was done lot around of the world and have to do more.

The purpose of this thesis is to gather information about the properties of critical solid fuels and fuel mixtures, to find out the problems caused by biomass power plants, especially boilers, and to find correlations between fuels and failures. These problems affect the availability of the power plant and maintenance costs, so the thesis also aims to create a procedure tools for continuous benchmarking and managing these problems.

This work was done for UPM Energy and its main target is to give references and information for the power plants of paper mills of UPM Kymmene Oyj. All references of this thesis have collected from field's literature and studies and users experiences from power plants.

2 PHYSICAL CHARACTERISTICS AND CHEMICAL COMPOSITION OF SOLID FUELS

The physical characteristics and chemical composition of solid fuels are very different in various fuels. For this reason, fuel properties determined agreed and standard methods, which indicate the availability of fuels. Composition of fuel can be divided into three parts: the combustible material, ash-forming inorganic matter and water. In Figure 2.1 can be seen fuel composition and main parts.

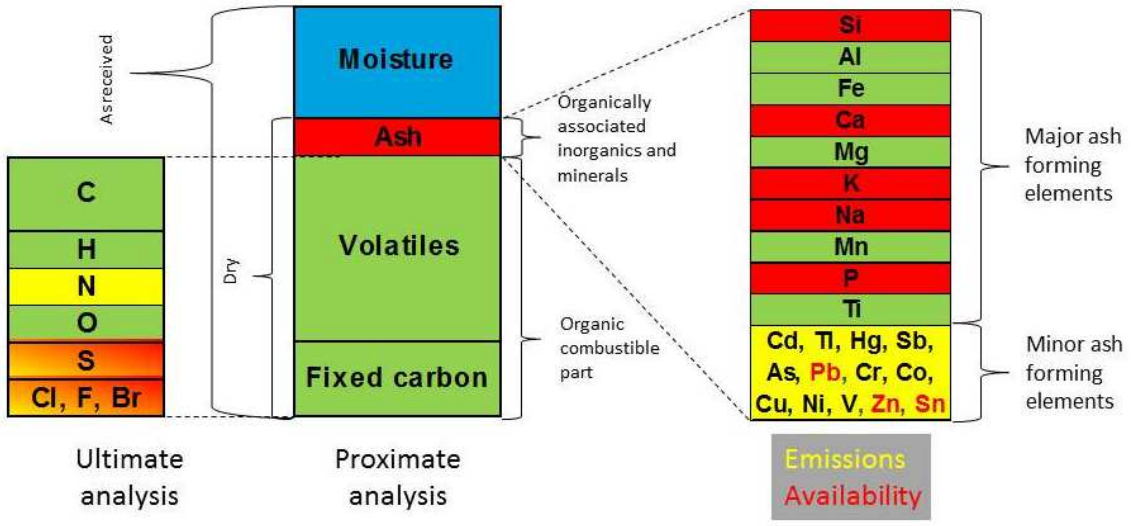


Figure 2.1 *Composition of fuel [3, p.4]*

Combustible material consists of carbon (C), hydrogen (H), nitrogen (N), oxygen (O), sulfur (S) and also some other elements, for example chlorine (Cl). Released from burning heat, the most important elements are carbon and hydrogen. Sulfur and nitrogen are environmentally hazardous substances because of the acid of the combustion product. The main technical characteristics of solid fuels are heating value, moisture content, volatile matter, ash content and composition, ash melting behavior and chemical composition. [4, pp.37-38]

Solid fuels can be divided into the fossil and renewable fuels. However, there are fuels with a placement between these two categories are still under discussion. Peat is generally calculated on fossil fuels, because it is a slowly renewable fuel. Different kind of recovered fuels, such as municipal waste is difficult to place in either group, as is includes both the fossil and the biomass component. [5, pp. 118-121]

By knowing the characteristics of available fuels, the production design is technically and economically realistic. In Table 2.1 can be find various values for different

kind of fuels. Values are suggestive range from different fuel databases, literature and power plants fuel analyses.

Table 2.1 *Typical properties of solid fuel [5, p.137; 6, p.26; 7; 8; 9; 10, p.6]*

		Wood	Bark	Forest residues	Straw	Sludge	Peat	Coal	RDF
Moisture	wt% (d.b.)	30-35	40-65	21-49	2-12	60-80	37-55	5-10	3-35
Ash	wt% (d.b.)	0.3-0.6	0.8-5.1	1.3-7	2-8	12-60	2.7-7.5	0.4-30	4-40
Volatile matter	wt% (d.b.)	84-88	70-80	82	68	45-97	65-80	27-33	70-90
LHV / Q_{net}	MJ/kg (d.b.)	15-20	5-19	17-20	16-17	8-22	19-26	26-36	12-40
C	wt% (d.b.)	30-50	50-66	45-54	40-50	25-66	50-56	60-90	48-75
H	wt% (d.b.)	3.5-6.5	4.6-8.4	4.5-6.9	5-6	4-7.5	5-6	3.5-6.5	5-10
N	wt% (d.b.)	0.1-2.3	0.1-0.8	0.4-1	0.5-5	<1.7	1-3.3	0.6-2	0.2-1.6
O	wt% (d.b.)	25-42	24-45	36-48	36-48	22-50	30-40	2-11	10-45
S	wt% (d.b.)	<0.05	<0.05	<0.1	<0.3	<1.5	<0.35	0.6-3	<1
Cl	wt% (d.b.)	<0.01	<0.03	0.01-0.1	0.2-0.6	<0.6	<0.06	<1.1	<1.5

As can be seen, the variation can also be a major within the fuel especially in biomass and waste fuels.

Initially, this chapter introduces the physical characteristics and chemical compositions and after that goes through fossil and renewable solid fuels. Finally, be introduced fuel quality classification.

2.1 Physical properties

Physical properties show the technical behavior of the fuels. They interact every step from purchase, storage, transport, combustion and finally to flue gasses. Table 2.2 shows different physical properties, especially for biomass fuels and their effect on different part of the process.

Table 2.2 *Physical properties of solid biomass fuels [11]*

Property	Effect
moisture content	storability, dry matter losses, LHV, self-ignition, plant design
heating values	fuel utilization, plant design
volatile matter	thermal decomposition behavior
ash content	dust emissions, ash behavior, ash utilization, combustion technology
ash melting behavior	operational safety, combustion technology, process control system, hard deposit formation
bulk density	fuel logistics (storage, transport, handling)
particle density	thermal conductance, thermal decomposition
physical dimension, form, side distribution	hoisting and conveying, combustion technology, bridging, operational safety, drying, formation of dust
fine parts	storage volume, transport losses, dust formation
abrasion resistance	quality changes, segregation, fine parts

These effects are also valid for fossil and waste fuels. The following four chapters present the key properties in more detail.

2.1.1 Heating value

Heating value is basic property about the combustion process, which tells how much heat energy can be released in complete combustion [5, p.122]. There are two kind of heating values: higher heating value (Q_{gr}, HHV), called gross calorific value (GCV) and lower heating value (Q_{net}, LHV), called net calorific value (NCV). Higher heating value describes the energy content in dry basis and lower heating value is calculated by subtracting the energy needed to evaporate the moisture content of the fuel. [6, p26] Heating value can be given in the dry basis with (d.b.), dry ash free (daf) or as received (ar). In ISO 1928 standard [12] higher heating value is obtained by performing the measurement in so called ”bomb calorimeter” in isobaric and temperature 25°C condition. There are also many approximate correlations, which describe different ways the heating values. Here are introduced some lower heating value correlations for solid fuel.

EN-14961 standard:

$$Q_{net,dry} = Q_{gr,dry} - 212.2 \times X_H - 0.8 \times (X_O + X_N) \qquad (1)$$

where

$Q_{net,dry}$ is the lower heating value for dry matter [kJ/kg (d.b.)]
$Q_{gr,dry}$ is the higher heating value for dry matter [kJ/kg (d.b.)]
X is the mass content of H, O, N [wt% (daf)]

$(X_O + X_N)$ can be calculated by substracting from 100 wt% the percentages of ash, C, H and S.

$$Q_{net,ar} = Q_{net,dry} \times \left(\frac{100 - m\%}{100}\right) - 0.02443 \times m\% \qquad (2)$$

where

$Q_{net,ar}$ lower heating value as received [MJ/kg (ar)]
$Q_{net,dry}$ lower heating value in dry basis [MJ/kg (d.b.)]
m% moisture content [wt% (daf)]

Dulong’s formula [13, p.53]:

$$Q_{gr} = 338.2 \times X_C + 1442.8 \times ((X_H - X_O)/8) + 94.2 \times X_S \qquad (3)$$

where

Q_{gr} is the high heating value in dry and ash free basis [kJ/kg (d.b.)]

X is the mass content of C, H, S [wt% (daf)]

Best when X_C is less than 86 wt%. [13, p.53]

Grumell & Davies –formula [13, p.53]:

$$Q_{gr} = (15.22 \times X_H + 937) \times \left(\frac{X_C}{3} + X_H - \frac{(X_O - X_S)}{8}\right) \qquad (4)$$

where

Q_{gr} is the higher heating value in dry and ash free basis [kJ/kg (d.b.)]
X is the mass content of C, H, S [wt% (daf)]

For peat [13, p.53]

$$Q_{gr} = 336 \times X_C + 1420 \times X_H - 153 \times X_O + 0.72 \times (X_O)^2 + 94 \times X_S \qquad (5)$$

where

Q_{gr} is the higher heating value in dry and ash free basis [kJ/kg (d.b.)]
X is the mass content of C, H, O, S [wt% (daf)]

Higher heating value is obtained reducing from the lower heating value the fuel hydrogen combustion generated water phase change effect. [13, p.53]

$$Q_{net} = Q_{gr} - 219.6X_H \qquad (6)$$

where

Q_{net} is the lower heating value for dry matter [kJ/kg (d.b.)]
Q_{gr} is the higher heating value in dry and ash free basis [kJ/kg (d.b.)]
X is the mass content of H [wt% (daf)]

It is possible to calculate higher heating value from the chemical composition of fuel in formula (7). [14]

$$Q_{gr} = 0.3491X_C + 1.1783X_H + 0.1005X_S - 0.0151X_N - 0.1034X_O - 0.0211X_{ash}, \qquad (7)$$

where

Q_{gr} is the higher heating value for dry matter [kJ/kg (d.b.)]
X is the mass content of c, H, S, N, O and ash [wt% (daf)]

In Table 2.1 were net calorific values for different kind of fuels. If it is compared coal with biomass fuels, biomass has lower heating value. It is because biomass fuels have more oxygen than coal, which decreases heating value. [6, p.26]

2.1.2 Moisture content

The moisture content is one of the main features of solid fuels technical characteristics, especially for biomass fuels. The reason is that, it influences directly the lower heating value of the fuel [5, p.121] and the volume of the flue gas produced per energy unit. It also increases fuel consumption. In Figure 2.2 can be seen the correlation between net calorific value and moisture content. With high moisture content, can be some problems with firing, for example ignition issues, the combustion temperature and quality of pyrolysis gases. [6, p.26] The more moisture there is in the fuel, the greater part of the release of energy in combustion used for water evaporation.

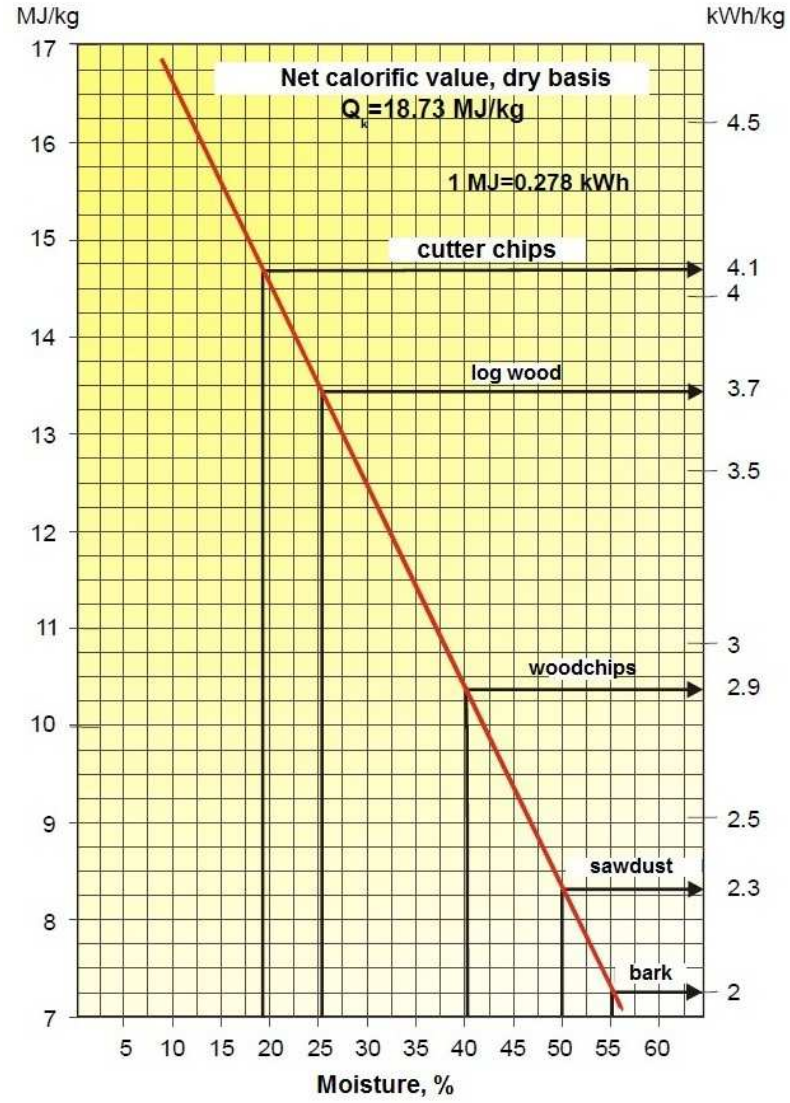


Figure 2.2 *Correlation between net calorific value and moisture content of woody biomass [7, p.150]*

Wood-based biomass can have water for more than 55 %, especially bark. Moisture content can be managed with storage and drying techniques before burning. The low quality and moist fuels can be burned without drying in the fluidized bed boilers. [4, pp. 39-40]

2.1.3 Ash content and ash melting properties

Ash of solid fuel is the mass of the inorganic material, which completely remains burning the fuel an oxidizing atmosphere [5, p.122]. Biomass ash content as a percentage of dry matter compared with the dry matter of coal and peat is smaller, which make it easier to ash handling and the costs of handling [7, p.37]. Because the heating values of biomass are small, the total of ash towards generated electric or thermal power is still high. Ash content is an important parameter which directly affects the heating value [15, p.181].

The chemical composition of the ash can be estimated for the melting and slagging facility. The main components of the ash of peat and coal are SiO_2, Al_2O_3 and Fe_2O_3 whereas the main components of the ash of wood are CaO, K_2O and MgO. The composition of the ash is strongly affected by the part of the plant e.g. the trunk, bark, branches and needles have different ash compositions. In particular it is important to know the composition of ash of waste firing in order to assess the potential limitations of their after-use. Bottom ash can be used under certain conditions for the manufacture of cement or building or earthworks such as the road base or as fertilizer (ash from wood). In Table 2.3 is presented the chemical composition of ash and Table 2.4 elemental analysis of the ash of variety biomass-based fuels.

Table 2.3 *Ash content and ash composition of different fuels, [wt% ash] [6, p.26; 9; 16, p.5]*

Fuel	ash content	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	P_2O_5	K_2O	Na_2O
sawdust	0.50 - 1.00	2.05	0.25	0.09	68.76	7.13	3.01	16.78	-
bark	3.30	10.74 - 14.00	2.80 - 3.20	1.40 - 4.96	45 - 60.16	5.20 - 5.82	3.40 - 5.24	3.80 - 8.69	0.9
forest residue	1.33 - 4.05	11.6 - 38.52	2.0 - 5.81	1.8 - 3.72	11.90 - 40	1.83 - 4.8	1.76 - 4.4	4.08 - 9.2	0.6
straw	4.86 - 5.88	53.10 - 62.06	0.19 - 3.60	0.17 - 1.20	4.48 - 21.10	2.13 - 3.00	2.52 - 4.10	13.59 - 30.00	0.03-10.50
waste wood	0.38 - 7.38	3.57 - 32.09	0.64 - 15.03	0.31 - 6.54	0.64 - 40.00	0.18 - 7.52	0.01 - 11.10	0.29 - 18.40	0.13-16.00
sewage sludge	2.80-63.57	17.86 - 38.30	0.80 - 9.89	12.50 - 36.65	9.10 - 20.60	1.12 - 2.80	13.10 - 19.61	0.70 - 2.20	0.36-5.00
RDF	1 - 44.20	8.91-57.11	6.80-27.80	0.98-9.98	7.00-44.07	0.63-5.64	0.07-2.10	0.2-2.82	0.20-2.82
peat	2.7 - 19	20.20 - 32.1	13 - 23.09	18.8 - 26.21	15.1 - 19.42	2.07 - 2.5	3.7 - 4.10	0.64 - 1.4	0.5
coal	0.4 - 40	46.48	24.60	8.43	6.83	2.62	0.48	2.34	0.40-7.30

Table 2.4 *Elemental analysis of the ash of variety biomass-based fuels [9]*

	Cl	Pb	Cd	Cu	Hg	Mn	Cr
	wt% (ash)	mg/kg (ash)	mg/kg (ash)	mg/kg (ash)	mg/kg (ash)	mg/kg (ash)	mg/kg (ash)
wood	0.15	34.5	1.7	123	0.1	6150	21.1
bark	0.07	52.1	4.3	111.5	0.3	8518	20.5
sludge	-	187	3.6	949.5	-	120	283
straw	2.45	3	0.1	55	0	90.5	7
peat	0.57	-	-	-	-	-	-
coal	0.01	-	-	-	-	-	-
RDF	2.8	-	-	-	-	500	-

The ash of the fuel does not melt at a certain temperature, but softens gradually on the solid liquid as the temperature increases. When the temperature rises, the ash formation starts and goes through four stages. [4, p.41] In Figure 2.3 is shown those stages.

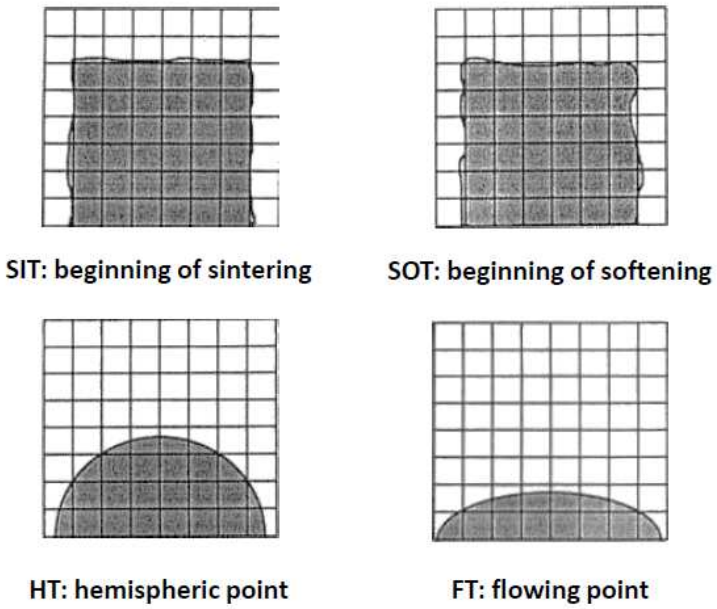


Figure 2.3 *Characterization of ash behavior. [18]*

Sintering (SIT) presents a process, where single ash particles stick together. During this process, the sample may change its original dimension without showing characteristics typical at the softening point. At the softening temperature (SOT), also known as deformation temperature, the sample shows the first signs of softening, e.g. surface changes, the rounding of the edges is complete and the sample starts filling the gas volume out between the particles. If the edges are still sharp, the shrinkage of the sample should not be regarded as softening. The hemispheric temperature (HT) gives the temperature when the sample takes on the approximate form of a hemisphere. The height of the melted sample is approximate half the length of the base line. At flowing point (FT) temperature the sample has shrunk to one third of its original height. [18] The next Table 2.5 is shown ash melting temperatures for different biomass fuels.

Table 2.5 *Ash melting properties of biomass ashes [9; 11, p.61; 18]*

Fuel	SIT, °C	SOT, °C	HT, °C	FT, °C
wood (hard)	780-1300	1100-1350	1150-1350	>1340
wood (soft)	1110-1340	1410-1640	1630-1700	>1700
bark (soft)	1020-1390	1100-1680	1270-1700	>1700
forest residue	1175-1180	1190-1205	1205-1230	1235-1250
waste wood	990-1335	1120-1340	1140-1500	1160-1700
sewage sludge	650-1120	1000-1180	1180-1480	1210-1490
mischanthus	820-980	820-1160	960-1290	1050-1320
straw	720-900	760-1000	1010-1150	1050-1290
grass	830-1130	950-1230	1030-1280	1100-1330

The melting points of various components of the ash vary widely, as can be deduced from Table 2.5. SIT temperatures are the most important, when is talk about ash related problems. When that temperature is overstepped, problems are occurring. A little amount of melting ash can contribute to problems in the boiler.

The amount composition, the melting and slagging behavior of ashes are great importance in combustion techniques, in which as ash removed in melt or where the melt ash may be deposited on the heat surfaces. The growing amount of ash decreases the heating value of the fuel, consumes fuel handling equipment, fouling on the heating surfaces of the boiler and can form corrosive deposits on the heating surfaces. [4, p.41] More about ash formation and the problems are described in more detail in Chapter 4.

2.1.4 Volatile matter

When the fuel is heated fast under inert atmosphere to about 900 °C, part of the fuel is gasified into hydrogen (H_2), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2) and other hydrocarbons. Fixed carbon is the residual substance. Gasified fuel components are called volatile matter. The amount of volatile matter depends on the geological age of the fuel. The older the fuel, the lower is the amount of volatile matter. For this reason, biomass fuels have high volatile matter, about 70-85%. It affects the amount of fuel ignition and combustion behavior of the flame formed. Plenty of volatile matter fuels ignite at lower temperatures. The ignition is faster; results are that the burning speed is faster and more complete. [4, p.40]

Volatile matter also affects the fluidized bed boiler furnace size. The majority of the combustion of biomass fuel is above the bed, where the volatile matter burns. Therefore, flue gas temperatures at the top of the furnace, superheaters and the cyclone of the circulated fluidized boiler are higher than for example the burning of coal.

2.2 Chemical composition

The chemical composition of biofuels has manifold effects on their thermal utilization and is affecting physical characteristics, combustion process and emissions. Certain elements in biomass deserve special attention. These include carbon (C), hydrogen (H), oxygen (O), chlorine (Cl), nitrogen (N) and sulfur (S). [6, p.24] There are also some

major elements (Al, Ca, Fe, K, Mg, Na, P, Si, Ti) and minor elements (As, Br, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Tl, V, Zn). This section focuses on the most important elements, but on the tables can also be found major and minor elements.

Concentrations vary depending on the origin and the type of biomass. Carbon, hydrogen and oxygen are the main components of the biofuels. In woody biomass include usually low amounts of N, S and Cl. The content of C and H affect positively to the HHV and the content of O_2 influence negatively. H also contributes to the LHV due to the formation of water. [10, p.977]

One the most important element, with regard to its behavior in different combustion related problems is chlorine (Cl). The high chlorine and alkali content of some biomass fuels can cause severe damage to the combustion units, especially corrosion. The high concentrations of chlorine are in RDF, straw, grasses and fruit residues. The Cl content of wood is generally low. [10, p.980] During combustion process Cl contained mainly forms gaseous HCl, Cl_2 or KCl and NaCl.

As you can see Table 2.1 higher concentrations of nitrogen ($N_{2)}$ are found in bark, logging residues, straw and RDF. During combustion process, the N is almost completely converted to gaseous N_2 and nitric oxides NO_x. [10, pp.977-979]

In different kind of fuels sulfur content is about 0-3%. In woody biomass is less or no sulfur, but in peat is very low sulfur content, about 0.2 %. Coal has very high sulfur content. [4, p.45] Sulfur is change in solid biomass usually forms gaseous SO2 and alkali. In Table 2.6 are collated different elements and their effects in the combustion process.

Table 2.6 *Effects of chemical elements [11]*

Property	**Effect to**
C	HHV
H	HHV, LHV
O	HHV
Cl	HCl-, PCDD/F emissions, corrosion, fouling, slagging
N	NOx-, N2O emissions
S	SOx emissions, corrosion, fouling, slagging
F	HF emissions, corrosion
K	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols, ash utilization (plant nutrient), fouling, slagging
Na	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols, fouling, slagging
Mg	Increase of ash melting temperature, ash utilization (plant nutrient), fouling, slagging
Ca	increase of ash melting temperature, ash utilization (plant nutrient), fouling, slagging
P	ash utilization (plant nutrient), fouling, slagging
Heavy metals	emissions, ash utilization, formation of aerosols

Elements including K, Na, S, Cl, P, Ca, Mg, Fe, Si are involved in reactions leading to ash fouling and slagging in biomass combustors [15 p.171]. More about problems in boilers are introduced in Chapter 4.

2.3 Solid fossil fuels

Coal, oil, peat and natural gas are counted in fossil fuels. This section concentrates on solid fuels, especially coal and peat. Several types of coal, including lignite and coal are used in energy production. Coal is an organic fossil fuel, which contains predominantly carbon and hydrogen, oxygen, sulfur, and additionally, for example, nitrogen, and some inorganic compounds. Coal is created over millions of years of flooding under forests and it has to be exposed to an oxygen-free state where microbes have shaped the organic matter as coal. Longer the process has progressed, higher the coal quality is. Older the coal is, greater is the carbon content.

Peat is mainly dead organic, plant-based materials which have been accumulated in humid conditions. The layers near the surface are more recent and it is growing about 1 mm per year. The deep layers are older. It is a slowly renewable resource that has many uses, especially for energy production. Peat producers are committed to the principles of wise use of peat lands. Most of the peat for combustion is currently produced by the milled peat method. In the beginning trees and the first surface layer are removed and the surface is ditched. Peat is milled 1-2 cm from the surface of the layer, which is then dried in the sun. When the moisture content of the peat is 50%, it is assembled mechanically. [4, p.31]

2.4 Solid biomass fuels

Biofuels are derived directly from living nature, resulting from plant photosynthesis through the masses. They can be liquid or solid. Usually liquid biofuels are called biofuels and solid biofuels biomass. They are renewable fuels, because they recur within a reasonable time, not more than a couple of hundred years. Biomass fuels are different from many of the characteristics of fossil fuels. Their special features are the low heating value, high moisture content and a large quantity of volatile matter. In addition, biomass fuel ashes are rich in alkalis.

Biomasses can be divided into various ways. In EN 14961: Solid biofuels. Fuel specifications and classes. Part 1: General requirements -standard solid biofuels are classified as origin and sources. Classification is divided into three groups: 1. Woody biomass, 2. Herbaceous biomass and 3. Fruit biomass. Woody biomasses are divided into separate sections for forest, plantation and other virgin wood (harvesting residues, whole trees, stumps), by-products and residues from wood processing industry (sludge, bark, sawdust) and used wood (untreated and treated wood). In Figure 2.2 is seen the diagram of how the woody biomass process goes.

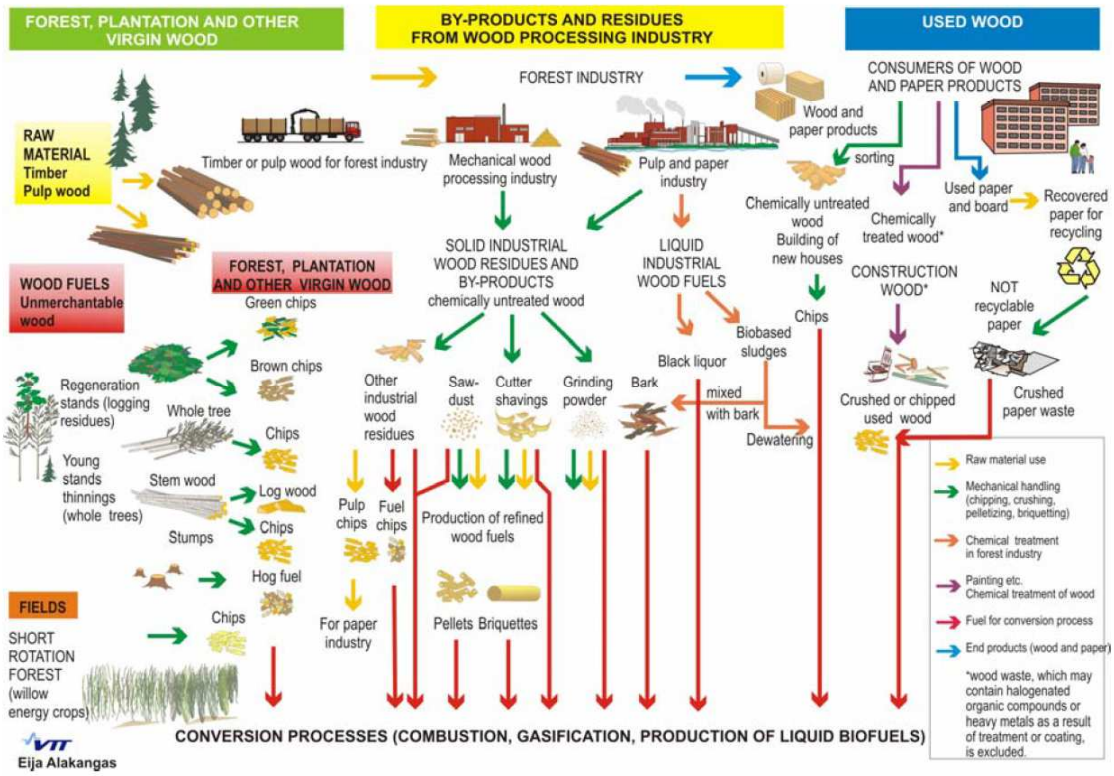


Figure 2.4 *Classification of woody biomass [19, p. 910]*

Herbaceous biomass includes for example cereal crops, grasses and oil seed crops. Fruit biomass includes orchard and horticulture fruits. Waste fuel is not always biomass, but waste wood and residues from processing industries of wood, herbaceous, fruit and agriculture are. Municipal waste and recovered fuel can include some fossil parts. More about waste fuels can be found in Chapter 2.5.

Biomass can be processed in different ways to improve their firing characteristics. Pelletizing is one method for finding more homogenous fuel if compared e.g. wood chips. Pellets are usually made of sawdust from wood processing industry. There are studies about making pellets from straw, reed canary grass, bark or the mixture of previous and peat. In pelletizing, the first process is drying the raw material to the moisture content of 10-15%. After that the material goes to the mixing chamber where the binder can be added. Form of pellets is obtained by pressing the raw material through holes in the matrix. Normally, pellets are about 5-30mm long and diameter is about 6-12mm. Finally, the pellets are cooled and sieved, to provide quality control. [20] Pellets heating value is about 15-17 MJ/kg. [4, p.29] Briquettes are made the same method as pellets, but they are bigger: length 10-200mm, diameter 50-80mm. Heating value of briquettes can be quadruple than normal moist wood chips, about 15-20 MJ/kg. [21]

Torrefaction is a thermal upgrading of solid biofuels. It means roasting at a high temperature (250 °C) under oxygen-free circumstances, when the water and part of the volatile compounds are leaving. During the process, loss of the biomass weight is 30%, but loss of the energy contained only 10%. Torrefied biomass has similar handling characteristics than coal. Torrefaction improve the biomass burning characteristics and heat-

ing value, and the development of its handling properties, so that it can be burned in existing coal-fired power plants. [22]

Lastly there is a summary table about biomass fuels. Table 2.8 includes different fuels, especially woody biomass, their main producers and suppliers, moisture content, particle size, impurities, ash content and also some regulations and standards which control their firing characteristic, for example particle size. There are some properties about processed fuel.

Table 2.7 *Properties of solid biomass fuels [11]*

Fuel	**Main producers and suppliers**	**Moisture content (wt-%)**	**Particle size**	**Impurities**	**Ash content (wt-% d.b.)**	**Regulations and standards**
Bark	sawmills, pulp and paper industry	40-65	extremely inhomogeneous fuel, 0.01-0.5 m	stones and soil, free of chemical impurities	non-contaminated bark 2-5, with mineral impurities 5-8	CEN TC 335, EN 14961
Sawdust	sawmills	fresh wood 40-60, after drying 10-20	<5mm	no or a very small amount	depends which kind of wood it is from, 04-1.1	CEN TC 335, EN 14961
Harvesting residues	forest farmers	fresh (right after harvesting) 40-60, storage for several months before chipping 30-40	chipped 20-80mm	mineral impurities, stones and soil	depends the amount of bark, 0.5 (softwood) - 2.5 (hardwood with bark)	CEN TC 335, EN 14961
Waste wood	wood producers, demolition wood	depends on its preceding utilization and storage, 10-30		paint, metal	depends the range of contaminations with non-wood compunds, 1.5-12	CEN TC 335, EN 15357
Straw	farmers	after 2-3 days drying 10-20	bales	chlorine, sulphur, potassium, nitrogen	3-12	CEN TC 335

After processing	**From**					
Pellet	sawdust, wood dust	<10	diameter 6-9mm, length 5-30mm	starch, maize in small quantities is allowed	<5	CEN TC 335, EN 14961
Torrefied wood	wood chips	<6			1,5-1,9	

2.5 Waste fuels

Demand for recovery fuels is increasing rapidly, while the price of conventional fuels is expected to continue to grow. Waste fuel can be produced for example from industrial production waste, commercial packing waste, demolition waste and municipal waste. Utilization of recovery fuel in Europe has been a common waste treatment method for a long time and its energy content has already been used since the 1970s.

Recovery fuels have many terms to use. Municipal Solid Waste (MSW) means a household, commercial and private and public services unsorted waste and in addition to that part of our industrial waste, which municipalities receive. In Finland, about 60% of municipal solid wastes are from households. Solid Recovered Fuel (SRF) and Refuse Derived Fuel (RDF) (in Finland Recovered Fuel REF) means to communities and businesses sorted and collected separately energy waste or mechanically produced waste fuel from municipal waste.

The burning material of waste fuel can be divided into fossil and biomass component parts. Part of the fossil fuel consists primarily of various plastics and a bit of rubber and textiles. Biomass part is mainly taking in of wood, wood-made paper and cardboard. In addition, biomass part may contain plants and animal fibers, textiles and food originate biomass. Recovered fuel is of varying quality, as well as burning quality and the chlorine and alkali contents can be high among others food residues. The typical detrimental elements of waste fuels can be seen in Table 2.8.

Table 2.8 *Typical detrimental elements of waste fuels [8, p.22]*

Impurity		Waste wood chips	Manufacture waste from industry	Waste from commercial and industry
Cl	wt-%	0,1	0,1	0,6
S	wt-%	0,1	0,2	0,3
N	wt-%	0,7	1,6	1,1
Na + K	wt-%	0,2	0,2	0,4
Hg	mg/kg	0,1	0,02	0,1
Cd	mg/kg	0,5	0,1	0,8
Zn	mg/kg	300,0	200,0	550,0
Pb	mg/kg	76,0	4,5	140,0
As	mg/kg	18,0	0,6	8,0
Co	mg/kg	41030,0	8,0	8,5
Cr	mg/kg	60,0	6,0	280,0
Cu	mg/kg	80,0	20,0	1150,0
Ni	mg/kg	10,0	4,0	100,0
V	mg/kg	2,0	1,0	7,0
Sb	mg/kg	10,0	10,0	300,0
Tl	mg/kg	0,6	0,6	0,6
Mn	mg/kg	100,0	25,0	160,0

Recovered fuels are necessary to crush for suitable size. In fluidized bed combustion the maximum dimension of the fuel is usually defined as 50-100 mm. In the manufacturing process, the fuel is cleaned up of various non-combustible materials as metal objects, glass, ceramics and stone material. The processing of recycled fuel is for a homogenized the composition. Waste fuel may also be pelletized. [8, p.40]

The experience of use of recovered fuels can be seen that the co-firing increase maintenance requirements of plant and thus maintenance costs. Additional investments are often needed for example for fuel delivery equipment, flue gas cleaning and emission monitoring equipment. Therefore, when considering the use of recovered fuels one has to remember that it is economically always the optimization of the cost of fuel and increased the maintenance costs of the range.

2.6 Classification of fuels

Different fuels have been created quality classification, which also limits the emissions of the combustion. This chapter presents the different fuel quality ratings, as well as the provisions of different countries.

Waste wood quality classification is based on the European standard for solid biofuels EN 14961. The same standard includes chemically treated by-products from wood industry and disposable wood. Wood waste is divided into four different categories. Class A is chemically untreated wood. Class B is chemically treated wood, with no heavy metals or halogenated organic compounds. Categories A and B are biofuels and they do not apply the directive (2000/76/EC) on the incineration of waste. Proper-ties of class A and B are classified according to EN14961-1. Category C of the wood is recycled fuel, and it can have heavy metals and halogenated organic compounds. Cate-gory C applies to a European solid recovered fuel standard CEN 15359, and waste regulations. Category D is hazardous waste.

The quality of recovered fuel affecting the manufacturing process, as well as composition of the raw material which are used solid recovered fuels requirements and technical specification classes in CEN 15359 is based on three main characteristics of recovered fuels. These include the economic factor (NCV), environmental factor (mercury content) and technical factor (chlorine content). The parameters of quality classes are shown in Table 2.9.

Table 2.9 *The parameters of quality classes for solid recovered fuel in CEN 15359*

	Net calorific value, MJ/kg	Cl, d.b. %.	Hg, mg/MJ	
Fuel class	average	average	median	80. percentage point
1	≥ 25	≤ 0,2	≤ 0,02	≤ 0,04
2	≥ 20	≤ 0,6	≤ 0,03	≤ 0,06
3	≥ 15	≤ 1,0	≤ 0,08	≤ 0,16
4	≥ 10	≤ 1,5	≤ 0,15	≤ 0,30
5	≥ 3	≤ 3,0	≤ 0,50	≤ 1,00

The economic importance of the heating value is therefore that the buyer wants fuel with the highest energy density. The concentration of mercury in recovered fuel is an important feature, because mercury is a dangerous heavy metal and it is difficult to clean from the flue gases. These three parameters of classes are defined in five grades with limit values. The combination of class numbers forms a class code. The parameters of classes are equally important. Properties must be read as a matrix: one of the recycled fuels is placed in NCV category 1, chlorine content category 3 and mercury content in class 2.

3 COMBUSTION PROCESS AND TECHNOLOGIES

Biomass combustion is a complicated process that consists of successive heterogeneous and homogeneous reactions. Various characteristics of the fuel fluctuate from each other, but the stages of combustion are the same for every solid fuel. The combustion process is a series of chemical reactions by which carbon is oxidized to carbon dioxide and hydrogen is oxidized to water. Most important aims in the combustion process are high efficiency, the reliability of the power plant and minimization of emissions. Temperature, time and turbulence (TTT) are three main needs for complete burning [23, p. 1513].

Solid fuels can be burned by the variety of different techniques, but generally the characteristics of the fuel determine the used technology. In this chapter is introduced the chemistry of the solid fuel combustion in the boiler. Finally we concentrate on combustion technologies, especially in biomass combustion.

3.1 Combustion of solid biomass fuels

Combustion of the fuel particle is separated to three stages: drying, pyrolysis/gasification and oxidation of the charcoal and the flue gases. The burning stages can happen at the same time. The particle surface can burn, when the middle is still moist. Burning time can be something from a couple of seconds to more than two minutes depending on the combustion technology. [4, p.83] In next chapters there are represented the stages of combustion especially for biomass, combustion reactions and the air demand ratio and finally the combustion efficiency and things that interact with combustion.

3.1.1 Stages of combustion

Initially, fuel particles are heated on the drying temperature (<100°C) and moisture removed away. Fuel moisture is an important factor in the boiler design because in the biomass the moisture content can be greater than half of the fuel mass. In this case, most of the combustion chamber must be reserved for the drying of moisture. Moisture removal can be accelerated by reducing the size of a fuel piece, or by increasing the evaporation area. Fuel moisture is evaporated, leaving a material consisting of a volatile and solids.

In pyrolysis (temperature 200°C-600°C) a wide range of gaseous products are released through the decomposition of fuel. In this stage fuel becomes combustible gases,

as non-reacted gas and the liquid phase are being the tar substances. Volatile materials catch fire and the reaction starts endothermically. When temperature increases for combustion, the reaction becomes exothermic. A portion of the solid part changes the gaseous and the residual solid substance is known the carbonized residue.

In the third stage (temperature ~800°C-1000°C) the residual carbon will burn on the surface without flame, when it has a sufficient temperature and sufficient oxygen. Ambient oxygen goes along with the surface of carbon, where it will react to form carbon monoxide and carbon dioxide. Moving away from the surface of the solid material, the carbon monoxide is oxidized after the supply of oxygen into carbon dioxide. The phase is low and the combustion will take from 50 to 70 percent of total rate of burning. [4, p. 83] In Figure 3.1 can be seen the process of combustion, especially for biomass.

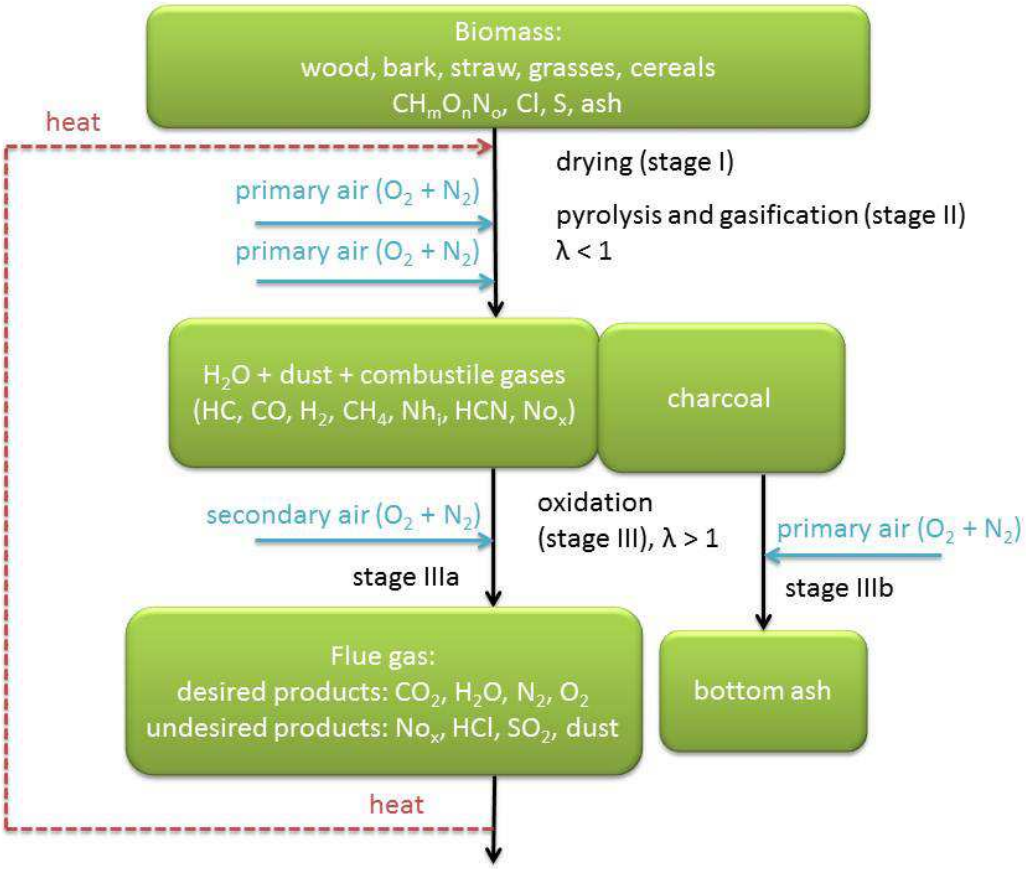


Figure 3.1 *Process of biomass combustion – principle [10, p.4]*

The rate of burning of a solid fuel depends on its chemical, structural and physical properties. The sub-processes affect significantly the firing, such as heat and mass transfer and chemical kinetics. Some of these processes may be slower than the others, which determine the rate of burning. [24, p. 186]

Maintain of combustion requires fuel, adequate temperature and oxygen. If one of these is missing, the combustion will stop. The main control method of the capacity of combustion equipment is adjusting the fuel flow, but also setting of process temperature and the import oxygen. [24, p. 186]

3.1.2 Air ratio and combustion efficiency

Fuels contain only carbon, hydrogen and sulfur for combustion components. If we want to consider the need for combustion air demand and flue gas composition, these elements reactions with oxygen must be known. The following are chemical reactions of combustion of the starting materials and final products. [4, pp.83-84]

$$C + O_2 \rightarrow CO_2 \qquad (8)$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad (9)$$

$$S + O_2 \rightarrow SO_2 \qquad (10)$$

Combustion reaction can be shown for the expected composition of hydrocarbons C_xH_y.

$$C_xH_y + \left(x + \frac{y}{4}\right)(O_2 + 3.76N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + 3.76\left(x + \frac{y}{2}\right)N_2 \qquad (11)$$

After drying, the main controlling parameter of the combustion process is the ratio between amount of air added and the amount of air necessary for a complete combustion of the combustible parts of the fuel. The air ratio is described with λ in combustion process. In Figure 3.1 can be seen λ and its effect on combustion stages. When the λ is below 1, gasification stage takes place and only a part of the fuel energy is converted into thermal energy. If λ is 0 pyrolysis is happening. When the λ is much more than 1, there is too much air and it will cool down the process. If the λ is equal to 1, the combustion happens at theoretical optimum or stoichiometric combustion. In real terms, this point is difficult to obtain due to mixing constraints between the fuel, flue gas and the air added and common value is 1.1-2.0, depending on the combustion technology. [10, p.2] As seen in Figure 3.1, primary and secondary airs are in two-stage combustion. This provides good mixing of combustion air and ensures an operation on lowest excess air as possible. [23, p.1512]

The optimizing of air demand when operating the boiler will minimize heat loss and improve combustion efficiency. Also minimizing flue gas flow improves combustion efficiency. The components of combustion and their effects on combustion efficiency and excess air ratio are represented n Figure 3.2. The NO_x curve goes nearly like the oxygen curve.

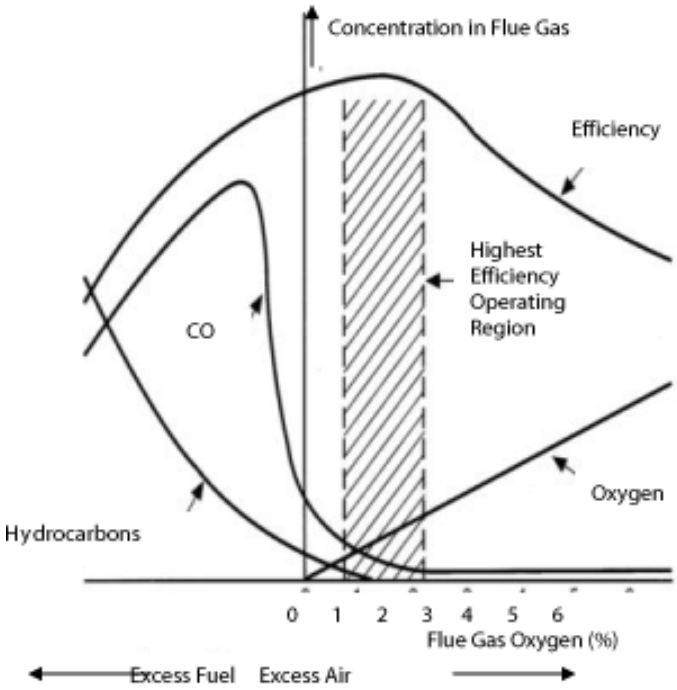


Figure 3.2 *Effects of components on combustion process [25]*

The combustion efficiency of a fluidized bed boiler (especially bubbling fluidized bed) is typically up to 90% without fly-ash recirculation. The efficiency depends on a great extent on the physical and chemical characteristics of the fuel as well as operating condition of the furnace. [26, p. 117] Some optimizing factors, which influence the combustion, are [11]:

- Air demand
- Fuel quality (fuel type, size, density, porosity, moisture, volatile and ash content)
- Combustion temperature (by flue gas recirculation or by cooled surfaces)
    - Too low: high CO and TOC emissions, poor char burnout
    - Too high: problems with slagging and ash deposit formation in furnaces
- Mixing of the flue gases in the furnace
- Residence time of the flue gases in the furnace
- Air staging and air distribution
- Process control (the process should be run as smooth as possible, no stop-and-go –operations)

3.2 Combustion technologies

Burning appliances function is to get the fuel to burn, in which case the fuel bound chemical energy is released as heat. In order to burn the fuel, the fuel and combustion air should be efficiently contacted with each other and the mixture is ignited. In biomass combustion, the fuel fractions should mix as well as possible. It improves homogenity of fuel and the mixture will burn better. Combustion efficiency must be good, so fuel

has to burn as perfect as possible, that excess air is the least possible. The combustion must take place in the combustor smoothly and in desired capacity and it can be adjusted when needed. Combustion devices have been developed in a variety of combustion characteristics of the fuels. [4, p.126] The next Figure 3.3 contains a variety of techniques and their applicability to specific fuels.

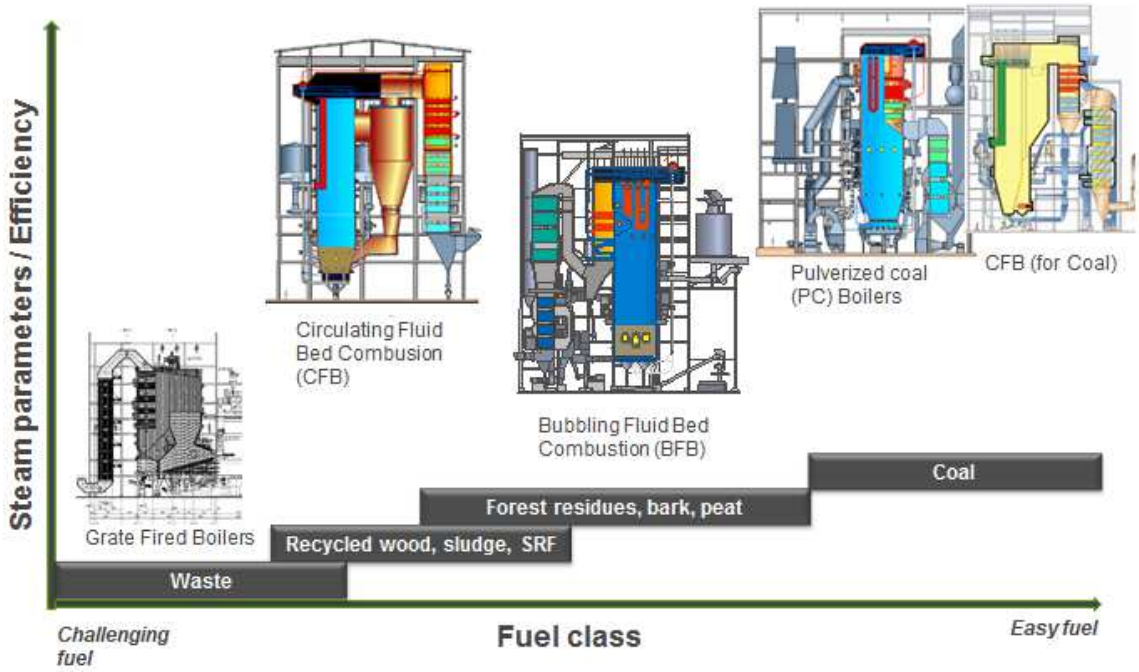


Figure 3.3 *Different combustion technologies for different fuels [27, p.12]*

On the basis of that figure, biomass and waste fuels are suitable for the grate fired boilers and fluidized bed boiler. In the past, mainly biomass fuels were burned in the grate. The problem is the worse burning result, efficiency and adaptation for the quality variations of fuels as well as higher emissions than the fluidized bed. Today fluidized bed combustion is regarded as the best burning technology for biofuels. In this work we focus only on fluidized bed combustion.

Fluidized bed combustion means combustion of a fuel non-reactive with the solid matter. As solid matter is normally used a granular solid material such as sand, limestone or ashes. In fluidized bed combustion fuel is combusted with the airflow through the glowing sand and the ash layer also known as bed. The fuel moves and mixes in the bed continuously, and gases and the heat transfer are very efficient. Fluidized bed combustion may be accomplished by the bubbling fluidized bed (BFB) and circulating fluidized bed (CFB).

Fluidized bed combustion is particularly suitable for low-quality fuels, whose combustion does not work in other ways without complex arrangements. Advantages of fluidized bed combustion are the possibility of using different fuels also simultaneously in the same boiler, inexpensive desulphurization and low NO_x and unburned gases. Pretreatment of fuel does not require just prior. Fluidized bed is also suitable for high mois-

ture fuels without further drying. In addition, the fuel and the rapid and large variations in quality may occur. The technology is significantly younger than the grate fired combustion and its commercial applications developed in the 1970s. [28, p. 490]

3.2.1 Bubbling fluidized bed

Fluidized condition comes about when the air is blown under fluidized bed material at suitable speed in the furnace. When the air velocity exceeds minimum fluidized velocity, the moisture of the particles of the bed is lost with each other and the particles begin to move relative to each other. When fluidized velocity increases will occur gas bubbles in a fluidized bed, which rise up. In this case, it is the bubbling fluidized bed. The bubbling fluidized bed is characterized by the clear top layer. The bubbling layer is one meter deep [29, p.2].

Fuel is fed onto the bed mechanically. Underneath conveyor of the fuel silo feeds the fuel through the feeder in the pipe, where it falls onto the bed. In order to divide the fuel to evenly over the bed area, are multiple feed horns used for fuel supply. In larger boilers the fuel supply comes from two sides of the wall. Before the fuel can be fed to the boiler, the bed is heated to a level (500-600 °C) that ensures a safe ignition of the fuel. The first warm-up is performed either in or on the bed with oil or gas heated burner. The bed temperature must kept so low that the ash of the fuel does not melt or even soft. Melt ash effect on sintering of bed material sand. The bed temperature is generally adjusted by recycling part of the flue gases back into the furnace. When the fuel is fed into the bed, it mixes with the hot bed material and catches fire. The volatile are burned on the bed, and the solid coal largely within the bed. Oxygen required for combustion is obtained partially from the fluidization air or primary air. In addition, part of the required combustion air is brought onto the bed as the secondary air. The end of the combustion takes place above the bed after the burning chamber with the secondary air. [4, pp.157–158]

A large heat capacity of the bed allows that this combustion method is suitable for high moisture content fuels and does not require drying. Mixed into the hot sand layer, the moisture fuel dries fast and heats up ignition temperature. The large heat capacity also evens out fluctuations in fuel quality. [4, p.157] Multiple fuels can be burn in the same furnace in a bubbling fluidized bed, such as industrial waste and wet fuels. [4, p.159]

At the bottom of bubbling fluidized bed furnace tubes are lined with a fireproof compound. Their function is to prevent the tubes from wearing caused by bed material, protect them from overheating and isolate the bed from cooling down too much. The bottom of the furnace is based on an air distribution grate to evenly distribute the fluidizing air to the bed. [4, p.158] The crosscut picture of the bubbling fluidized bed boiler can be seen in Figure 3.4.

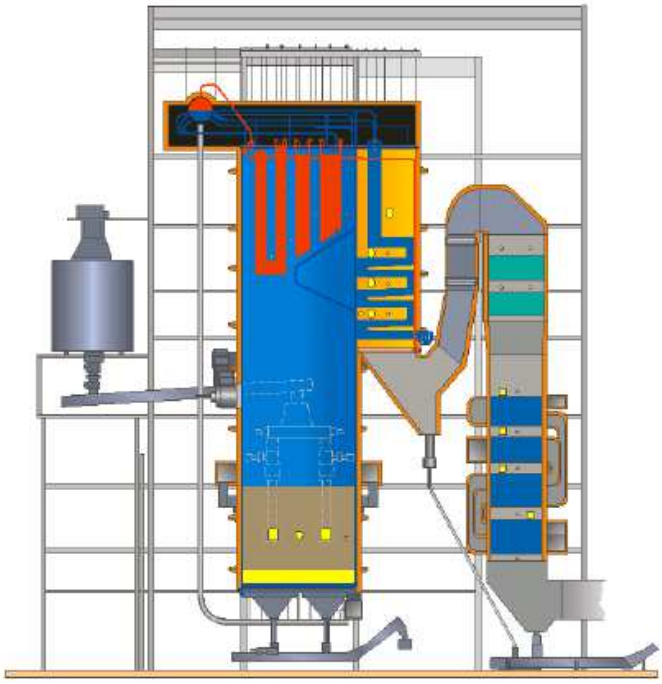


Figure 3.4 *Crosscut picture of BFB boiler [30]*

3.2.2 Circulating fluidized bed

When fluidized velocity increasingly grows, the bubbles disappear, and the fluidized bed layers clear surface and particle loss from the layer increases. When the speed is raised above the terminal velocity of particles or the free velocity, begins increasing proportion of the particles travel upwardly along with the gas flow. This is called the circulating fluidized bed.

In the bed of the circulating fluidized bed boiler does not stand out as a clear surface, but the bed density decreases as a function of the height when a part of the sand drifts along flue gases. From the combustion furnace exits gas stream with the particles and they are separated by the cyclone and returned to the furnace. [4, p.159]

Fuel is fed to a boiler or sand which is separated in the cyclone. In general, the latter method is used commonly. The combustion air comes into the boilers by primary and secondary air. The primary or fluidized air comes through the bottom nozzle. Secondary air is led into the fluidized bed at couple different levels from a few meters above the grate. For boiler start-up, the boiler provides the same start-up burners as the bubbling fluidized bed. The advantages of circulating fluidized bed combustion are low NOx emissions and an option of affordable desulphurization from flue gas. Since the combustion temperature is low, the NOx formation will be minor. Still wanted to reduce NOx emissions, the boiler can be fed ammonia. Sulfur emissions reductions can be done with limestone injection. Limestone reacts in the flue gas with the sulfur compounds to form gypsum. The gypsum is removed from the boiler with ash. [4, pp.161-162] Figure 3.5 shows the crosscut picture of the circulating fluidized bed boiler.

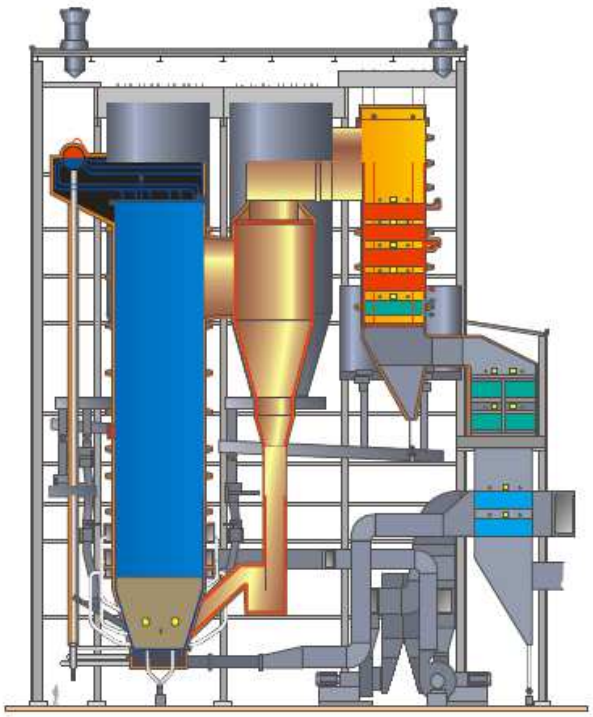


Figure 3.5 *Crosscut picture of CFB boiler [30]*

3.2.3 Material issues

Boiler materials should be highly resistant to high temperatures and a range of problems affecting the boiler. A good selection of materials and the understanding of their behavior in a fluidized bed environment are critical to the operators. One of the heating surfaces of the boiler, the superheater has the most challenging material choice due to high temperature. The temperature of the steam in superheaters may be up to about 550 ° C. The used metal of superheaters has to be hot strength and creep resistance must be good. In addition, the used metals must withstand the fire and they may not be inclined to hot corrosion. [4, p.188]

The duration time of material of the superheater is significantly reduced with increasing temperature. It is important to avoid overheating, for example effect on the pan scale or uneven flow. Carbon steels and low alloyed steels have high thermal conductivity, which makes them suitable material for the superheater, where the pressures and temperatures are not high. These materials can be used for industrial process boilers and small power plants. [4, p.193]

High temperature strength can be improved by the combination of various substances. One of the active blend components is molybdenum. The dimensioning of pressurized parts strength up to specific temperature happens according to the yield stress. Yield stress decreases with increasing temperature. If the substance is in a constant strain, over a certain temperature, its shape changes in lower stress than yield strength and over time the substance can break down. This slow deformation of the material is

referred as the creep and the creep causing tension limiting creep stress. To the creep stress affects the temperature and time. [4, p.192-193]

Temperature is not only constraining value of material choosing. Corrosion resistance as well as strength, ductility, availability, and the cost are all factors that must be considered when selecting a material. Problems with biomass and recovered fuels give high requirements for example of corrosion resistant of material. Choosing right material for high temperature heating surfaces is also the optimization problem. When making the selections, one has to take into account what the fuel palette is. As the problems with biomass and recovered fuels are known, one has to choose a material which goes good together with the requirements of the fuel palette. This is not so easy optimization, because the fuel palette can be changed lately. When the new fuel fractions are coming to the palette, it has to be tested with the chosen material and study, if the fuel fractions are proper for the material or if material changes should be made. Selecting metals for their resistance to corrosion should be considered as a part of the overall material selection process.

3.3 Co-firing

Co-combustion is a way to burn biomass with some fossil fuel, in general with coal, oil or peat. It can be advantageous with regard to cost, efficiency and emissions. There are three ways of co-utilization: Co-combustion or direct co-firing, where the biomass is directly fed to the boiler. Biomass can be preprocessed such as dried, grinded or impurities removed before feeding. Indirect co-firing: The biomass is gasified and the gas is fed to the boiler. Parallel combustion: The steam of biomass combustion is used together in a power plant with the main fuel, but the biomass is burnt separate from the boiler for steam generation. [23, p.1518]

Co-firing can bring many positive effects in power plants operation and emissions, even the different fuels can be competitors in the fuel market. When the plant is using a wide range of fuels and a number of fuel sources, transport distances and costs will decline. SO_x and NO_x emissions usually decrease due to the lower sulfur and nitrogen content in biomass than in coal. Alkali components in biomass ash can have an effect of SO_x removal. Biomass has a high volatile content; it can also be used as reburn fuel for NO_x reduction from the coal combustion, which gives a further potential for the significant decrease of the NO_x emissions. NO, NO_2 and N_2O can be substantially reduced by the co-firing of biomass in coal-fired fluidized bed boilers. [23, p.1518] The moisture of wood chips tends to rise too high during the winter just when the boiler is required full power. Peat moisture content is lower, 40-45% in winter, so the boiler capacity can be increased by increasing the proportion of peat fuel mix. Co-firing with other biomass fuel helps to control peat combustion carbon dioxide and sulfur emissions and from sometimes associated the fouling of the boiler and hot corrosion in the combustion of wood chips. [31, p.25] Co-firing of biomass is the most economic technology to reach the target of CO_2 reduction.

There are also some negative effects: the additional investment cost for biomass pretreatment and boiler retrofitting, higher operation cost due to increased fouling and corrosion. The ash quality can be negatively affected mainly by alkali metals and chlorine contained in biomass. [23, p. 1519]

4 ADVERSE EFFECTS AND TECHNICAL CHALLENGES OF COMBUSTION

When fuel particles are drying, pyrolyzing and burning, they release a large number of particles and gases. Besides the main components of the flue gas (O_2, N_2, CO_2, CO, SO_2, and NO_x) nascent flue gases contains a number of gaseous substances or compounds, which may condense on the chemical reactions or cooling of the flue gas. In addition, the particles of flue gas size and composition will vary. Other substances of fuels, such as inorganic compounds and minerals can stay in solid particles in combustion and leave with the bottom slag, vaporize and connect with other flue gas particles or migrate with the flue gases.

The problems with inorganic material of the unburned fuel in the combustion process are the largest single cause of unforeseen shutdowns of boilers and premature wear. Ash-forming constituents release in the combustion process and ash behavior varies greatly from the fuel and combustion technology to another. The biggest problems in the combustion of demanding fuels are high temperature chlorine corrosion, slagging and fouling on the heat delivery surfaces, the hardening of bed and generated emissions. Different problems in BFB are shown in Figure 4.1.

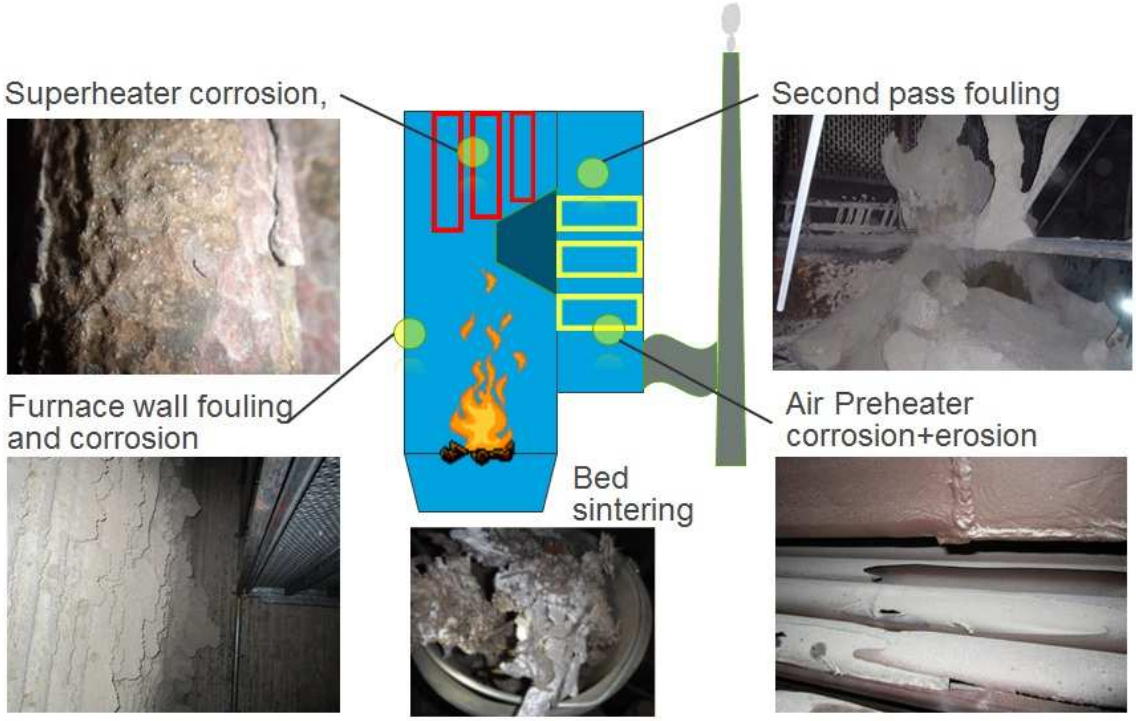


Figure 4.1 *Different problems in BFB boiler [27, p.16]*

The release and behavior mechanisms of the ash are known best for carbon pulverized fuel firing. Other fuels and combustion methods research information has increased in recent years, when biomass and recovered fuels are more widely used.

The availability of different fuels can be compared with each other with fuel analyzes and various indexes. Fuels are different from their tendency to cause usability problems in boilers, as can be seen in Figure 4.2. The most common problems are fouling, slagging, corrosion, bed sintering and the hardening of the bed. The greater the probability is, the more difficult the fuel is. [32, p.5]

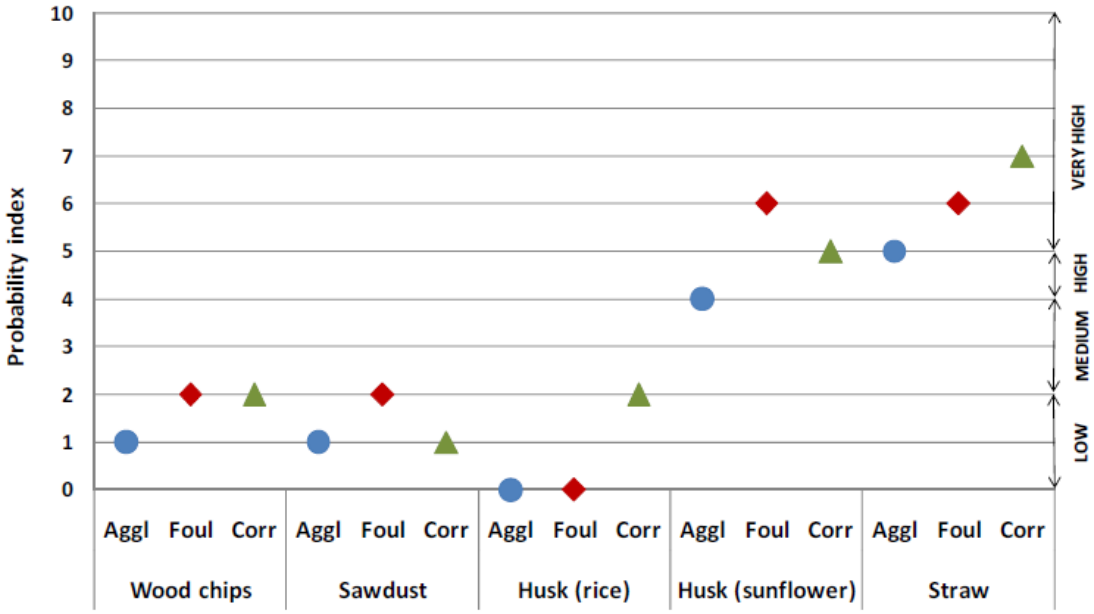


Figure 4.2 *Agglomeration, fouling and corrosion tendency for different types of biomass fuels [32, p.4]*

Differences in biomass with fossil fuels are the characteristics of a wide variety, low energy density, high moisture content and low nitrogen and sulfur content. Biomass moisture content and particle size have a large effect on the combustion process and thereupon on combustion efficiency. High chlorine and alkali (potassium in wood fuels) contents are cause of fouling and the corrosion of the boiler. Biomass ash content is generally low, but its melting point is lower than that of fossil fuels. In Figure 4.3 are listed different fuels and their relative fouling feature. As can be seen recovered fuels have more fouling features than coal, peat and pure wood fuels.

Figure 4.3 *Relative fouling of fuels and their ashes in fluidized bed combustion [8]*

Because different fuels are burned often mixed in the fluidized bed boilers, the fuel and ash interaction is difficult to accurately assess in advance. The composition of the fuel mixture and fuel mixture ratio effect on the problems and knowing the composition is one main issue when is talk about problems in boiler. Coal and peat with high sulfur content and with inert ash of the fuel mixture usually facilitate the fouling problems of the boiler burning biomass and recovered fuels. In different fuels ash forming ingredients vary widely in composition and quantity. Proportion of inorganic substances, for example the trunk of the tree is a few percent, whereas some coals may contain ten percent ash.

Knowledge of generation and behavior of problems are essential when moving challenging fuels that give rise to such problems easily. When the mechanism of formation of ash particles is known, the choice of the fuel mixture, boiler construction, as well as process optimization and design influences the composition of the ash particles, the size, the transmission of heat transfer surfaces and particulate emissions. Emissions from combustion, the formation of ash and the challenges and problems caused by them are discussed in the following sections.

4.1 Emissions

When fuel is burned, flue gas properties are particularly affected by the chemical composition of the fuel. Combustion of the fuel generates organic materials: carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter and water vapor. In addition, to the flue gases will move the gaseous and vapor substances depending on

fuel composition and the combustion process. These substances are hydrogen chloride (HCl), hydrogen fluoride (HF), carbon monoxide (CO) and a variety of metals, which are harmful to the environment and people. Therefore combustion conditions and flue gas cleaning will be designed with particular care. [33, p.371]

4.1.1 SOx

During fuel combustion the main part of the sulfur reacts with oxygen forming sulfur oxides SO_2 and SO_3. The sulfur trioxide in the flue gases reacts with the water to form sulfuric acid, H_2SO_4. If the sulfuric acid vapor of the flue gases gets to condense on the boiler heat transfer surfaces, results it in their rapid corrosion. Corrosion can be prevented by keeping the temperature of the flue gas on the back of the boiler above the dew point. Sulfur dioxide released into the atmosphere is causing sulfur depositions, which cause acidification of soil and water. [4, p.92] Sulfur content in biomass is very low, as shown in Table 2.1. Combustion of biomass does not pose boiler and environmentally harmful sulfur emissions.

4.1.2 NOx

In the combustion process nitrogen oxides (NO, NO_2) are generated when nitrogen and oxygen react with each other. In the furnace they consist mainly of nitrogen monoxide, which is then oxidized to nitrogen dioxide as the temperature drops. In general, however, the total NO_x emissions are counted. The NO_x emissions are acidifying environment in the same manner as SO_2. Formation of emission can be made smaller by bringing down the temperature of the boiler and the flame and reducing the oxygen content of the flame by following means: flue gas recycling, increasing heat transfer surfaces, reducing air in pre-heating, phased combustion as well as NO_x reduction with natural gas. [4, pp.92–94]

4.2 Formation of ash

The inorganic residue, ash, from the unburned fuel, is the largest single cause for unforeseen shutdowns of boilers. The problems are usually caused by the sum of many different factors. The whole formation of ash must be taken into account when looking at ash-related problems. Different stages of the formation of ash can be seen in the next Figure 4.4.

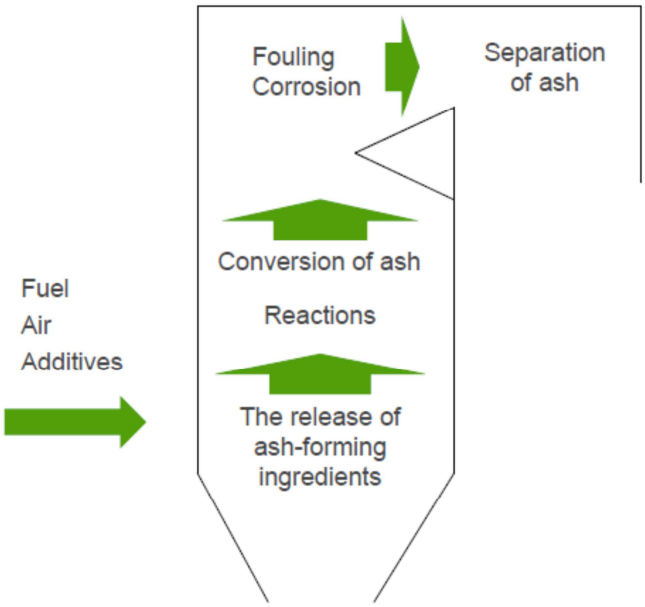


Figure 4.4 *Different stages of ash formation in boiler [34, p.269]*

Most of the ash-forming constituents remain in burning coke. They form one or a few solid ash particles at the end of combustion. In this manner an ash particle size is about 5-100 micrometers. The residual ash of coke is forming mineral particles and inclusions, whose typical elements are silicon, iron, aluminum, calcium, magnesium, and potassium. However, some of the particles escaping from the burning coke are released into the flue gas. Ash particles or aerosols can be less than one micrometer of a size. The alkali and alkali earth compounds, chlorine and sulfur have been found to release the fuel latter way. [34, p.273] Ash formation during the biomass combustion is presented in Figure 4.5.

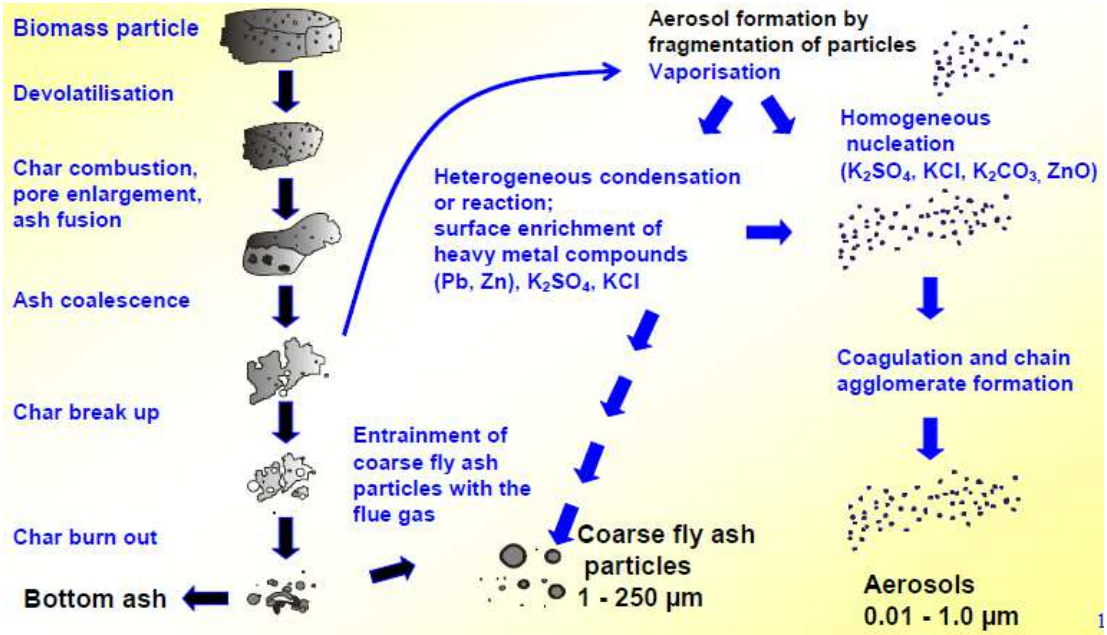


Figure 4.5 *Formation of ash during biomass combustion [35, p.15]*

Another important ash-forming components mechanism of delivery is vaporization from the burning particle. The particles which are released in that way have high pressure steam compounds, such as alkali chlorides and hydrogen chlorides. The evaporation leads the small, less than one micrometer-sized particles in condensing. Both steam and particles formed of them are very reactive and react easily with other ash-forming ingredients. Different fuels have different particle size distributions of fly ashes and they are shown in Figure 4.6.

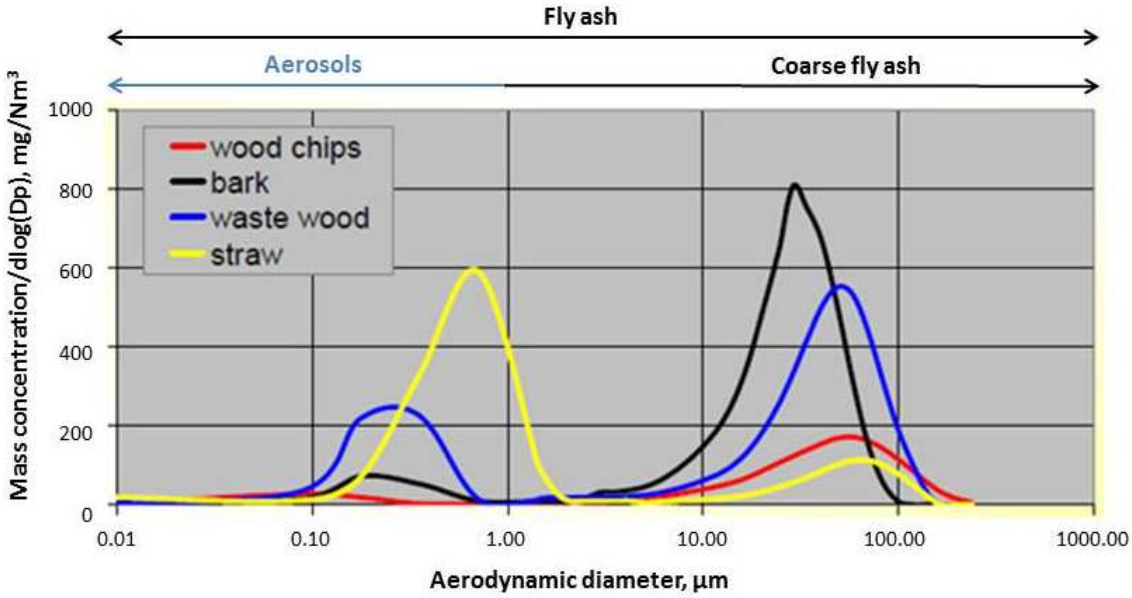


Figure 4.6 *Particle size distributions of fly ashes from biomass combustion [35, p.16]*

The problems of the ash in the pulverized firing boiler are different from the problems in the fluidized bed boiler, because the temperature in the furnace is lower than in fluidized bed boiler, thus reducing the melting tendency of the ash particles. Also the number of evaporated ash-forming constituents in fluidized bed boiler is smaller than the same fuel in pulverized firing boiler. In addition ash problems caused by dirt deposits formation are in the fluidized bed boilers problems like fluidized bed sintering and subsequent agglomeration. The sintering of bed material means the integration of bed particles without actually melting. In this case the fluidized bed consists of unfluidized areas and local hot spots. As a result of the hot spots sintered particles are melted and agglomerates are generated. Fluidization is disrupted and in the worst case the agglomeration will ultimately lead to boiler shutdown. [36, p.21] Ash related problems can be occur, when there are little amount of melting ash.

4.3 Slagging and fouling

The heat delivery surfaces of boiler fouling and slagging are caused mainly by the fuel containing non-combustible inorganic residue, ashes, and the behavior of the combus-

tion process. Melted ash stick to the heat delivery surfaces of the boiler and scorification happens. It is called slagging. Fouling happens, when scorification is in convection parts of the boiler. [34, p.275] Layers in the circulating fluidized bed are generally formed to the cyclone and the return duct from the cyclone, whereas the layers in the bubbling fluidized are bed formed the heat surfaces of the flue gas duct. Heat delivery surfaces are fouling, above all, in the furnace and convection superheater. Also on the surfaces of the air preheater and economizer may form layers, but they are typically thin and loose, and do not cause any problems. Fouling of the heat delivery surfaces is affected by the temperature of the gases and the ash melting temperature and composition slagging and fouling mechanisms, effects and limitation of problems are examined in the following sections.

4.3.1 Condition of formation

Slagging is contamination in the heat delivery surface areas of the furnace. Disturbed are radiant superheaters, where surface temperatures are higher than the tubes. Slag layers in the furnace are typically thick, and the surface is often clearly melted. Ash particles are transported to the heat surfaces usually by hitting.

The partially molten ash particle sticks very effectively on the pipe. Generally, this kinds of infectious particles consist of alkali silicate, alkali- and earth alkali sulfates, alkali chlorides or mixtures of those. Although the melting points of the substances as pure compounds in many cases exceed 1000 °C, the mixture starts to melt in some cases at 500 °C. There are not exact melting points for the mixtures, but melting occurs gradually in a temperature range that can be hundreds of degrees. From the sticking of ash and the layer point of view the most critical temperature range of flue gases is the one where the ash particles are 15-70% melted. It is referred as the T_{15} and T_{70} temperatures of ash. If a particle is completely solid or only a small part is molten when the particle reaches heat delivery surface, the particle will bounce back easily to flue gas stream and thus does not form deposits. In this case the flue gas temperature of flue gas (T_{FG}) should be below the T_{15} of ash. If the ash particle is sufficiently melted or when the flue gas temperature is higher than T_{15}, it adheres to the heat delivery surface. This kind of layer can grow, in principle, infinitely thick. If the particle impacts on the surface while it is almost completely or completely melted or when the surface temperature exceeds the ash T_{70}, the particle no longer increases the layer but flows out along the surface. [34, pp.279-280] The mechanism of formation of the deposit is shown in Figure 4.7.

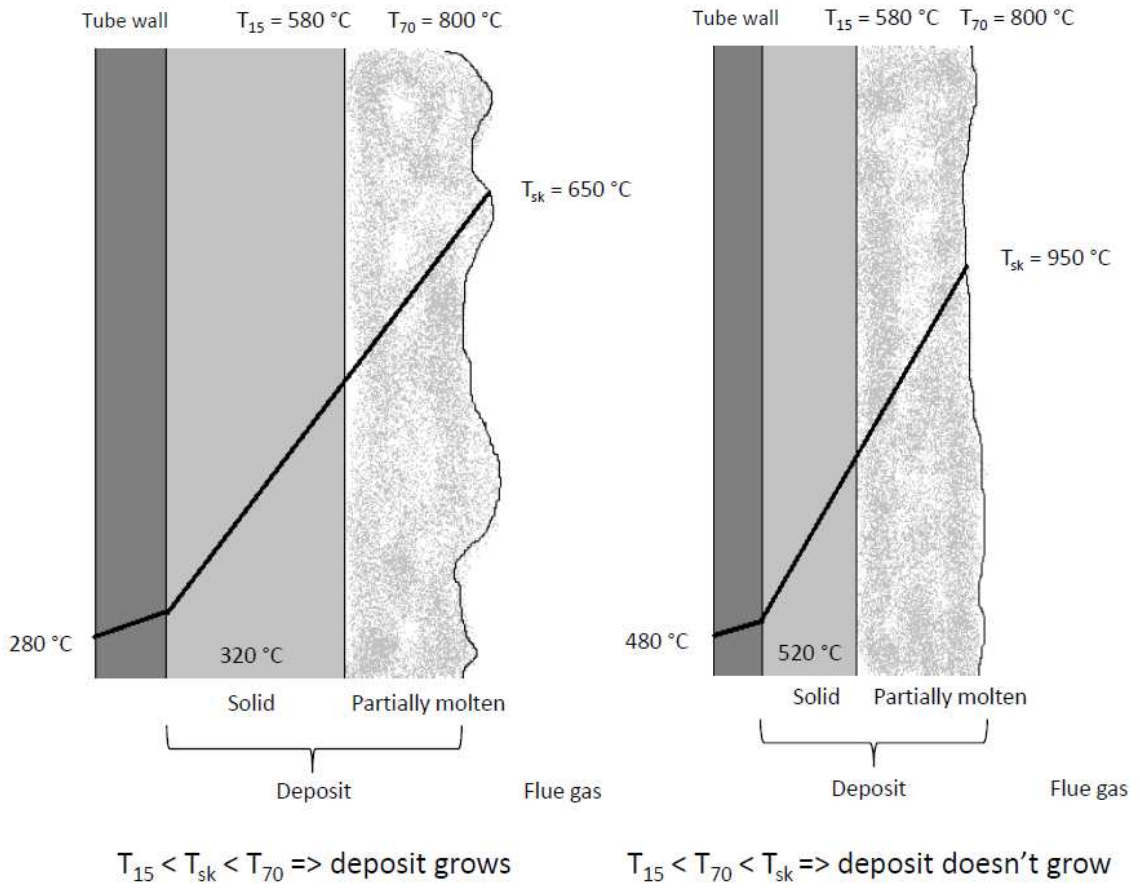


Figure 4.7 *Mechanism of formation of deposit. In left deposit grows and in right deposit doesn't grow. [34, p.280]*

The heat delivery surfaces fouling means the formation of deposits on the boiler convection sections. Ash deposits are formed to convection surfaces mainly in solid forms in SIT temperature and they generally grow slower than the molten state slag in the sediments. Deposit formation usually starts with a thin initial deposit. Accumulated particles on the surface have reached the surface of different types of diffusion mechanisms. Other particles grabs on the initial deposit and over time they will grow more strongly attached to the surface. The characteristic of this type of deposit is slow hardening or sintering. Ash composition, particle size, temperature, time and composition of the surrounding flue gas affect the sintering. [4]

The fuel and ash compositions impress substantially the fouling of ash. Also amount of ash affect the fouling. Fine, reactive calcium and alkali metals containing ash are more fouling than in the main silicate minerals containing ash. Reactive calcium and alkalis are organic compounds, carbonates (e.g $CaCO_3$, $NaCO_3$ and KCO_3) or salts (e.g., NaCl and K_2O) occurring in the fuel. In fuel combustion these react to oxides, sulfates and chlorides (CaO, Na_2SO_4 and KCl). In particular, the melting points of the chloride salts are relatively low; on the account chlorine of the fuel grows the fouling of ash.

Characteristics of the fuel and the ash besides the combustion conditions and the boiler structure affect the boiler fouling. The high combustion temperature inflicts on

the melting of ash and creates more adhesion in the ash to heat delivery surfaces. The same effect is created by poorly managed, uneven combustion. High superheater temperatures and superheaters, which are exposed to combustion heat radiation increases the adhesion and hardening of the ash.

4.3.2 Effects

Dirty layers of heat delivery surfaces reduce heat transfer from the flue gas to cooling material flow, which is taken into account in the design of heat delivery surfaces. Dirt makes the coefficient of thermal transmittance of the heat exchanger worse and a certain heat power transfer requires a higher temperature surface. In practice the dirty heat delivery surfaces are seen from rising flue gas temperature and reducing live steam temperature. A dirty heat exchanger cools the flue gases less and heat transfer to steam weakens. The drop of live steam temperature due to the fouling of the superheater is a particular problem in biomass-fired power plants. When dirty layer grows, too hot flue gases may lead to overheating of the heat delivery surfaces. In addition, a thick dirty layer blocks the heat delivery surfaces and inflicts the flow resistances to flue gases in the boiler. Heat exchanger pressure losses or the end temperature of the flue gas rising can be seen as a sign of dirtiness of the heating delivery surfaces and dust removal is needed. [4, p.209]

Direct collision adhesion of solid ash particles not often cause serious problems, because layers of dirt can easily be removed from heat delivery surfaces. However, the surfaces need dust removal often enough so that the ash particles do not have time to cling to each other with sintering. Removal of sintered layers from heat delivery surfaces is much more difficult than the removal of loose ash. [4, p.209]

4.4 Corrosion

Corrosion means the weakening and destruction of the material caused by reactions between a material and its environment. Typically fluidized bed boiler corrosion is caused by fuels with high chlorine content, poor combustion control, high temperature gas, local atmosphere reducing or tube surface erosion. [26, p.312]

Corrosion protection of metals at high temperatures is often based on protective characteristic of the metal oxide layer, which is formed on the metal surface. Chromium, molybdenum, aluminum and silicon are typical additives whose purpose is to improve the corrosion resistance of the oxide layer. Damage of the oxide layer and thereupon deterioration of corrosion resistance is usually a result of local reducing conditions the molten ash deposits formed in the boiler or heat delivery surfaces. Particularly serious the situation is, if the same context is also associated with sulfur or chlorine compounds, which contribute to corrosion. Chlorine is the biggest cause of corrosion in oxidizing and sulfur under reducing conditions. Combustion takes place mainly in oxidizing conditions. Biomass fuels have low sulfur contents, so sulfur is not a problem. In

general, the chlorine levels are low in biomass fuels. An exception is the rapid growth biomass. Especially straw contains a considerable amount of chlorine. [4, 34]

4.4.1 Mechanism of the high temperature chlorine corrosion

The most common corrosion mechanism is the hot corrosion of superheaters in the combustion of biomass and recovery fuels in the fluidized bed boiler. It is caused by the fuel chlorine together with alkalis, usually potassium in wood based fuels and natrium in recovery fuels. When fuel is burning, chlorine and alkalis of ash are reacting to alkali chloride salts like NaCl and KCl. If some sulfur content fuels are added to the furnace, sulfur becomes oxidized sulfur oxide and it reacts with NaCl and KCl when they are in the flue gasses. Under the circumstances NaCl and KCl does not condense on the surface, but chlorine is carried along with HCl to flue gas cleaners. [8, p.43] In flue gas, alkali chlorides appear as melt droplets and vapor. When alkali chlorides confront the superheater surface, their vapor condenses and droplets adhere to the surface. The melting temperature of the salt mixture when forming on the pipe is considerably lower than the melting temperatures of the individual components of the salt. Chloride salts break the protective oxide layer of the pipe and starts the chlorine corrosion. Provided that, the pipe surface temperature is sufficiently high. Chlorine corrosion begins to occur significantly at temperatures of 500-600°C. Also, the corrosion rate increases significantly with increasing temperature. Figure 4.8 shows dependence of the corrosion rate of flue gas temperature and the surface temperature of the pipe material. At low superheated steam and saturated steam does not occur corrosion in superheaters. However the fouling of the ash is not reduced.

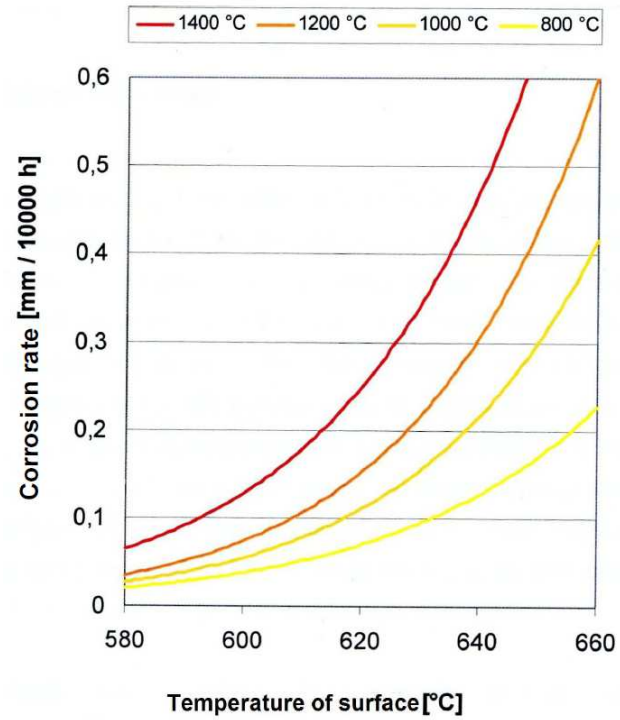


Figure 4.8 *Corrosion rate is dependent on temperature of pipe material surface [36]*

Basic influencing factors on chlorine corrosion are:

- chlorine content in the flue gases
- temperature of flue gas
- sulfur content of fuel
- material of superheater
- temperature of material of superheater

In the next Figure 4.9 is shown chlorine and sulfur corrosion mechanisms.

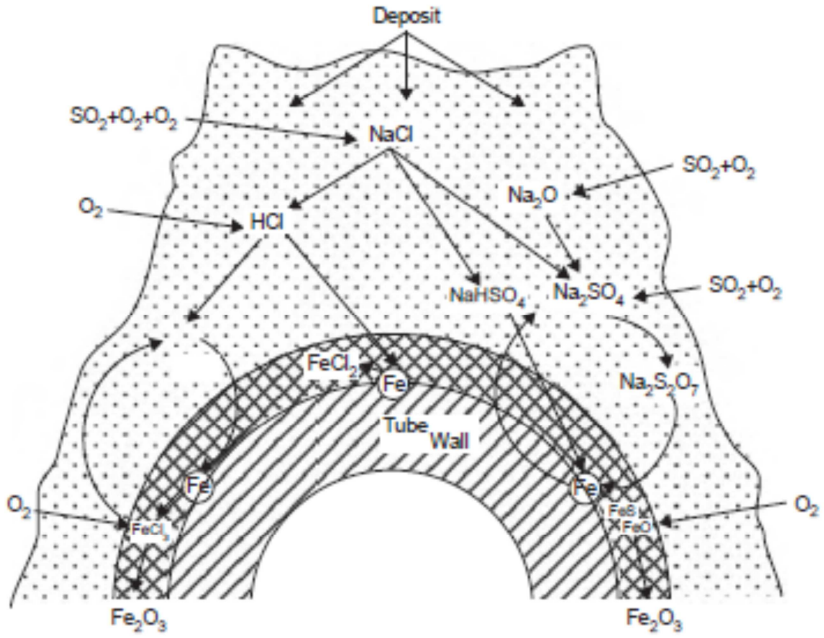


Figure 4.9 *Chlorine and sulfur corrosion mechanisms. [4, p.314]*

Thickness of the ash layer on the surface of superheater increases with time. Chlorine encapsulates between the deposit and the tube surface when the chlorine corrosion continues. On the surface of the tube chlorine reacts with iron forming ferric chloride ($FeCl_2$), which is easy to volatile. On the surface the diffusible ferric chloride is oxidized outer to iron oxide (Fe_2O_3) and the released chlorine is transported back to the tube surface. Some of the chlorine diffuses out of the tube through the deposit. However, a new chlorine alkali diffuses to tube surfaces with alkali chlorides and corrosion continues. Over time, close to the surface of the tube form a layer of pure crystal sodium chloride and potassium chloride. Because of chlorine encapsulation, chlorine corrosion will continue a long time in the furnace even if the chlorine content fuel burning will be finished. [8, p. 44]

Table 4.2 *Corrosion systems and melting temperatures [35, p.23]*

System	Melting temperature, C°
NaCl	801
KCl	772
$FeCl_2$	677
$CrCl_2$	845
NaCl-$FeCl_2$	370-374
KCl-$FeCl_2$	340-393
NaCl-$CrCl_2$	437
KCl-$CrCl_2$	462-457

Bark and wood burning boilers have a chlorine corrosion risk already in low chlorine content of the fuel (~ 0.1% of the dry matter) when the steam temperature exceeds 500 ºC. When the chlorine content of the fuel increases, chlorine corrosion can occur even at steam temperatures from 460 to 480 ºC. Recycled and demolition wood fuels can also contain in heavy metals that decrease the melting points of the salt mixtures. Such impurities are in particular lead (Pb) and zinc (Zn). Steam of recycled fuel fired boilers temperature is usually limited to less than 460 º C. [8, p.44]

4.5 Erosion

Boiler erosion means wearing caused by small and hard particles of the flue gases. The velocity of erosion is affecting by the velocity of particle V_p and the angle α, in which a particle impacts the surface. Figure 4.10 describes the erosion process. The process of erosion is similar to the metal cutting.

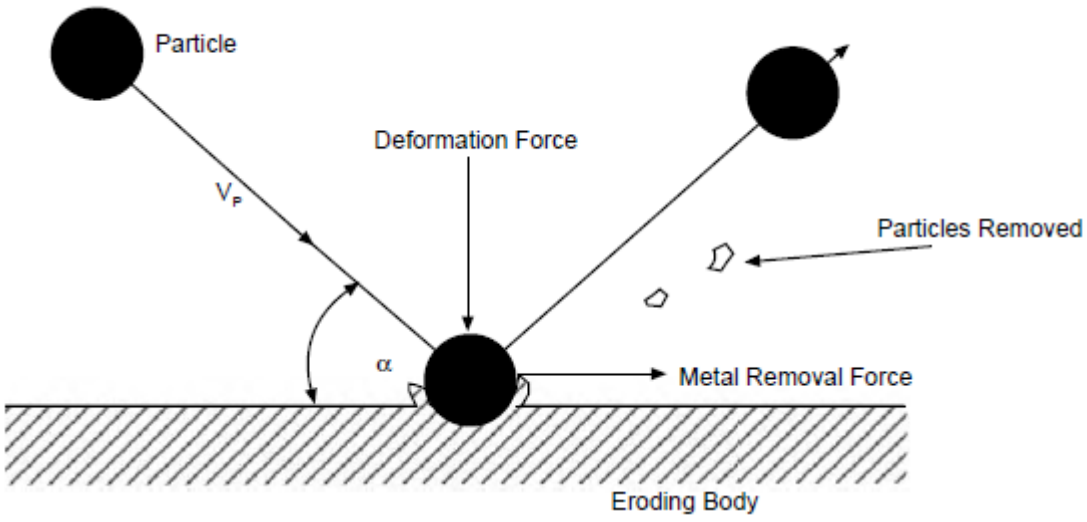


Figure 4.10 *An eroding particle hits a target metal surface causing deformation and removes the deformed piece. [26, p.302]*

Erosion is affected by the following three major factors: 1. Flow and environmental conditions, 2. Particle properties, 3. Nature of target materials.

Erosion is not considered as difficult problem as corrosion, if the fuel does not include plenty of erosive particles such as peat. Peat and its ash have significantly hard and erosive quartz compounds and that is why erosion should be taken into account in peat burning. Erosion can be slowed by reducing flow rates, by avoiding too sharp turns in the pipes as well as building large enough smoke and flow paths or by using protective walls. [4, p.213, 26, p.306]

4.6 Controlling of problems

Management of deposition is a key issue to achieve the high availability of a power plant. That is why the boiler must be designed and implemented in such a way that fouling is limited to an acceptable amount. Fluidized bed boilers burn the mixture of different fuels and there by the fuel and ash interaction is difficult to estimate in advance. Coal and peat are sulfur containing and inert ash fuels, which generally facilitate the boiler fouling problems, when co-firing with biomass and waste. Such inert silicate ash thin down ash, which is alkali, catchy and fouling. Then deposits are more brittle and easier to remove. Silicate ashes are mildly abrasive, which removes ash deposits like light sandblast. Peat and coal are recommended to be burned in boilers with recovery fuels.

Removal of slagging areas from heat delivery surfaces is much more laborious than the removal of solid ash particles. Molten layers on metal surfaces are problematic because they contribute to the corrosion of boiler tubes. Sticking of the molten ashes to the heat exchanger after combustion furnace can be prevented by keeping the end temperature of the flue gases at the top of the furnace 40-50 °C lower than the sintering (SIT) point of ash. [4, p.209] Impurities collect easily to bed sand so changing bed sand more often helps the problems in the boiler.

There are good solutions to limit the difficult fouling. The combustion furnace must be large enough so that the particles leaving with gas flow have time to burn completely before they are removed from the furnace. Recommended is also a large empty open cooling channel between the furnace and the heat exchanger, where only the walls are the heat exchanger. The flue gas is cooled in this chamber enough for the ash of the flue gas at the end of the channel not to be sticky and a significant part of gaseous compounds to have time to condense and separate from the flue gas. Typically, the flue gas temperature should be after the empty chamber less than 650 °C. [37, p.52]

After the open chamber, the first placed superheater design will be such that the flue gas impurities do not block it easily. This point is often used in superheater design. The heat exchanger surfaces are installed at a long distance from each other and the same direction as the gas flow goes. The form of the flue gas channel system must be such that the gas flow velocity is as constant as possible. Water and steam flows of heat exchangers must be smooth, so overheated points do not form to the surfaces of the ex-

changer. Moreover accumulated deposits are typically cleaned from the boiler once a year. [37, p.52]

To reduce fouling the use of additives which increase the ash melting temperature is also studied. Possible additives include aluminum oxide (Al_2O_3), calcium oxide (CaO), magnesium oxide (MgO), dolomite ($CaMg(CO_3)_2$) and clay. These materials enrich the ashes and prevent the emergence of alkali. For example, three percent increase in the clay mixed with straw burning raised the ash softening temperature of 770°C to over 1200°C [38, p.15].

High-temperature corrosion can be prevented by using the additives and superheater materials that contain high levels of chromium, nickel and molybdenum. The technical solutions of the boiler can be used to a greater distribution of the tubes of superheaters, and connecting the superheater by downstream, which decreases the material temperatures. Usage of the curtain tubes before superheaters decreases the flue gas temperature. [8, p.45] Reduction of temperature can be made by flue gas circulation in the secondary combustion zone. [39, p.4]

4.6.1 Controlling indexes

There are lots of different suggestive relations, indexes, between fuels and problems based on the chemical composition of fuel, ash and flue gases. With those indexes problems with ash and flue gases can be estimated. In Sommersacher's article [40] and Obernberger's presentation [11] fuel indexes are derived from chemical fuel analyses. They are checked and evaluated regarding their applicability by measurements performed at lab- and real-scale combustion plants for a large variety of fuels. There are also slagging and fouling rates [34, p.296]. Here are those indexes and their limiting values.

1. **K + Na + Zn + Pb is an indicator for aerosol emissions (fine particles smaller than 1 µm) and deposit buildup on heat exchanger surfaces**
   If the sum of K, Na, Zn, Pb is increasing in the fuel, the aerosol emissions and deposit buildup usually increase. Low emission rage is <1000 mg/kg d.b. values (e.g. softwood), medium emission range is 1000-10000 mg/kg d.b. values (e.g. hardwood, bark, waste wood) and high emission range is >10000 mg/kg d.b. values (e.g. grass, pellets and straw).

2. **Molar 2S/Cl ratio is an indicator for corrosion risk**
   The probability of corrosion can be estimated from the sulfur/chlorine ratio. When the fuel 2S/Cl ratio is more than 4, chlorine corrosion is considerably reduced. The sulfur in fuel is oxidized to sulfur dioxide and it is reacting with the metallic chloride (NaCl and KCl) while they are still in the flue gas. Thus, metallic chlorides do not condense on superheater surfaces, but chlorine is drifted as HCl to the flue gas cleaner.
   2S/Cl > 8 low corrosion risk

Mainly sulfates are formed an initial deposit layer directly on the tube surface acting as a protective layer against Cl-induced corrosion
4 < 2S/Cl < 8 moderate corrosion risk
Since the reaction SO_2 -> SO_3 in biomass furnaces is chemically limited and since additionally $CaSO_4$ is formed, the theoretical minimum of 2S/Cl = 0,5 isn't sufficient to build up the protective layer and to avoid Cl-condensation on the tube surfaces
2S/Cl < 4 high corrosion risk

3. **Si/(Ca + Mg) and (Si + P + K)/(Ca + Mg) indicate ash-melting temperatures**
   Ca and Mg increase the ash-melting temperature

4. **Slagging ratio R_s, alkali/acid-ratio (ash) x S (wt-% in fuel)**
   The ratio describes the effect of different elements of ash on formation of slagging in radiation area of boiler.

$$\frac{Fe_2O_3+CaO+MgO+K_2O+Na_2O}{SiO_2+TiO_2+Al_2O_3} \times S_{tot} \qquad (12)$$

   < 0,6 low slagging tendency
   0,6 – 2,0 moderate slagging tendency
   2,0 – 2,6 high slagging tendency
   > 2,6 very high slagging tendency

5. **Fouling ratio R_f, alkali/acid-ratio (ash) x Na_2O (wt-% in ash)**
   The ratio describes the effect of different elements of ash on formation of fouling in convection area of boiler.

$$\frac{Fe_2O_3+CaO+MgO+K_2O+Na_2O}{SiO_2+TiO_2+Al_2O_3} \times (Na_2O)_{ash} \qquad (13)$$

   < 0,2 fouling is insignificant
   > 1,0 forecast disturbed fouling

4.7 Economic effect of problems

The problems of combustion of biomass affect the power plant investment, operating and maintenance costs. To prevent the problems must expensive process, structural and material solutions, as well as equipment purchases be made. Use of various additives increases the operating costs as well as increased consumption of bed sand. Due to problems, the need to make different kinds of maintenance is arising, when the maintenance costs of plant rise. The following Table 4.3 reviews factors that increase the cost in the various problems.

Table 4.3 *Increasing factors of various problems [27, 36]*

Problem	Cost factors	Investment cost	Operating cost	Maintenance cost
Slagging and fouling	▪ structural solution of boiler: size of boiler, area of heating surfaces, disposition of superheaters	X		X
	▪ dust removal: number, type, demand		X	X
	▪ control of temperatures		X	
	▪ decrease of end temperatures		X	
	▪ material choosing	X		X
Corrosion and erosion	▪ material choosing	X		X
	▪ structural solution of boiler	X		X
	▪ consumption and feed of additives	X	X	X
	▪ speed-up renewal of heating surfaces	X	X	X
Emissions	▪ consumption of additives		X	X
	▪ expense of device			X

Fluctuations in fuel prices, as well as cost of the plant caused by damages should be optimized according to the need. In Figure 4.11 fuels are settled in the figure to proportion to the challenging and the price of the fuel.

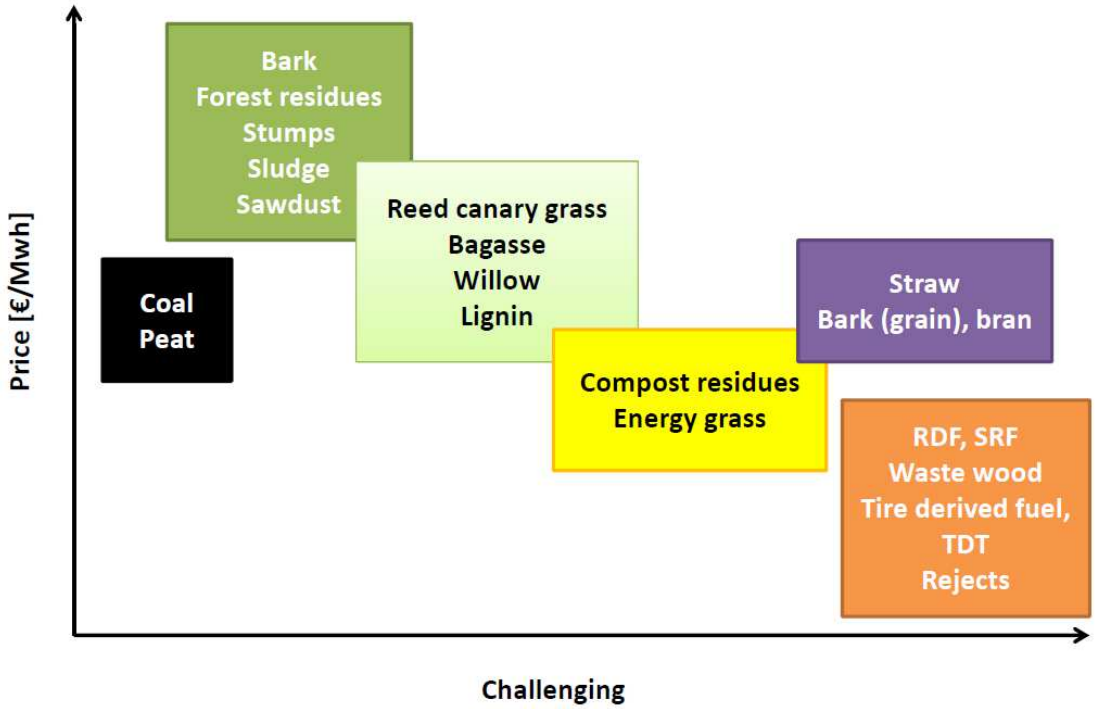


Figure 4.11 *Dilemma of fuels and prices, reproduce [3]*

In some situations it is more advantageous to accept a number of problems, which have a clear solution than change fuels to cleaner but more expensive ones. The plant must assess what types of problems are acceptable and which are not.

5 ESTIMATION TOOL OF FUEL MIXTURES

Knowing the properties of the fuel mixture is one of the most important matters to estimate problems in boilers. The properties of the fuel mixture should be chosen so that the effectiveness of their use in the boiler is maximal. Properties are difficult to verify because the more challenging the fuel is the less reliable samples can be received. The estimate can be made from literature values or previously received samples for every fuel fraction or mixture. The development of technology has brought with it the real-time measurements of the properties of the supplied fuel. It is important to know the properties of the fuel mixture when new controls or maintenance are made to the boiler or new boiler is introduced.

This estimation model gives the suggestive estimation of the properties of the fuel mixture. It can be based on the own data of the user or values of the fuels from literature. The tool gives the properties of the fuel mixture. After that the model compares results giving fuel indexes and limiting values and provides an estimate if some problems occur or not. This gives the potential to find out the problems of the selected biomass mixture and to further evaluate the technical and economic impact of the problems. This model is made with Microsoft Excel 2010 program. User has to give the following data for the calculation (all the values are for the dry basis):

- Proportion of whole mixture [%]
- Moisture content [wt%]
- High heating value [MJ/kg]
- Low heating value [MJ/kg]*
- Low heating value, as received [MJ/kg]*
- Volatile matter [wt%]
- Ash content [wt%]
- C content [wt%]
- H content [wt%]
- O content [wt%]
- N content [wt%]
- S content [wt%]
- Cl content [wt%]
- Major (Al, Ca, Fe, K, Mg, Na, P, Si, Ti) and minor (As, Br, Cd, Co, Cr, Cu, F, Hg, Mn, Ni, Pb, Sb, Ti, V, Zn) elements

*Can be calculated from HHV.

Also composition of ash is needed for estimate problems:

- SiO_2 [wt%]
- Al_2O_3 [wt%]
- TiO_2 [wt%]
- Fe_2O_3 [wt%]
- CaO [wt%]
- MgO [wt%]
- Na_2O [wt%]
- K_2O [wt%]
- P_2O_6 [wt%]
- SO_3 [wt%]

The next chapters will introduce the calculation method for this model and some test results.

5.1 Calculation method

First task is to calculate the composition of the fuel mixture. When the composition of the one fuel type and its proportion of the whole mixture are known, weighted average for the mixture can be calculated. In Excel, this formula is SUMPRODUCT().

$$\bar{x} = \frac{w_1x_1+w_2x_2+\cdots+w_nx_n}{w_1+w_2+\cdots+w_n} = \frac{\sum_{i=1}^{n} w_ix_i}{\sum_{i=1}^{n} w_i}, \quad (14)$$

where

n is number data
x_i is data values ($x_i > 0$)
w_i is weighted rate ($w_i > 0$).

Estimation tool calculates weighted average for every value. Then can problems with indicators and limiting values be estimated. Lower heating value as received can be calculated from higher heating value with formulas (1) and (2). If the user puts in only the higher heating value, the tool calculates lower heating values and uses calculated value. If the user puts in the lower heating values, it uses that.

5.1.1 Limiting values

In Chapter 4.6.1 is introduced some indexes which can suggestive estimate some problems in the boiler. There are also technical requirements from the boiler supplier, which have to be taken into account if user wants to avoid problems. Technical requirements for each boiler and also some universal indicators have been used in this estimation tool.

The tool can be modified unique to the need of power plants. Own limiting values and indicators, which are important for that power plant can be put. With technical requirements boiler works well and any critical problem will not happen. Table 5.1 gathers technical requirements of the fuel mixture for those four boilers, which will be introduced in Chapter 6.

Table 5.1 *Technical requirements of fuel mixture for BFB-boilers [27]*

		A	B	C	D
Moisture	wt%		32 - 48		32 - 55
LHV (as received)	MJ/kg		5,8 - 7,2		5,2 - 7,2
N content	wt%		0,2 - 0,6		0,2 - 0,7
S content	wt%		0,02 - 0,10		0 - 0,15
Ash content	wt%		29 - 34		25 - 40
Cl content	wt%	< 0,02	0 - 0,1		0 - 0,15
Na + K	wt%		< 0,2		
Al + Sn + Zn + Pb	mg/kg		< 100	< 560	
Zn + Pb + Sn	mg/kg		< 500	< 460	
F	mg/kg	< 10	0 - 25		
Br	mg/kg	< 8			
Cd + Ti	mg/kg	< 4	< 7	< 7	< 7
Hg	mg/kg	< 0,25		< 4	
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V	mg/kg	< 900	< 900	< 1060	< 900
Fe	g/kg			< 7	
$Na_2O + K_2O$	wt% ash	< 20			
$(Na_2O + K_2O)/(75*(Na + K))$	g/kg	< 0,35			

Earlier introduced molar 2S/Cl ratio estimates corrosion risk. It can be calculated when sulfur and chlorine content in the fuel are known. First we have to calculate the amount of substance of sulfur: how many molar of sulfur there is per gram of dry fuel.

$$n_S = \frac{x_S}{M_s} \quad (15)$$

where

n_S is amount of substance of S [mol/g_{fuel}]
x_S is the content of S [wt%]
M_s is molar mass of S [g/mol].

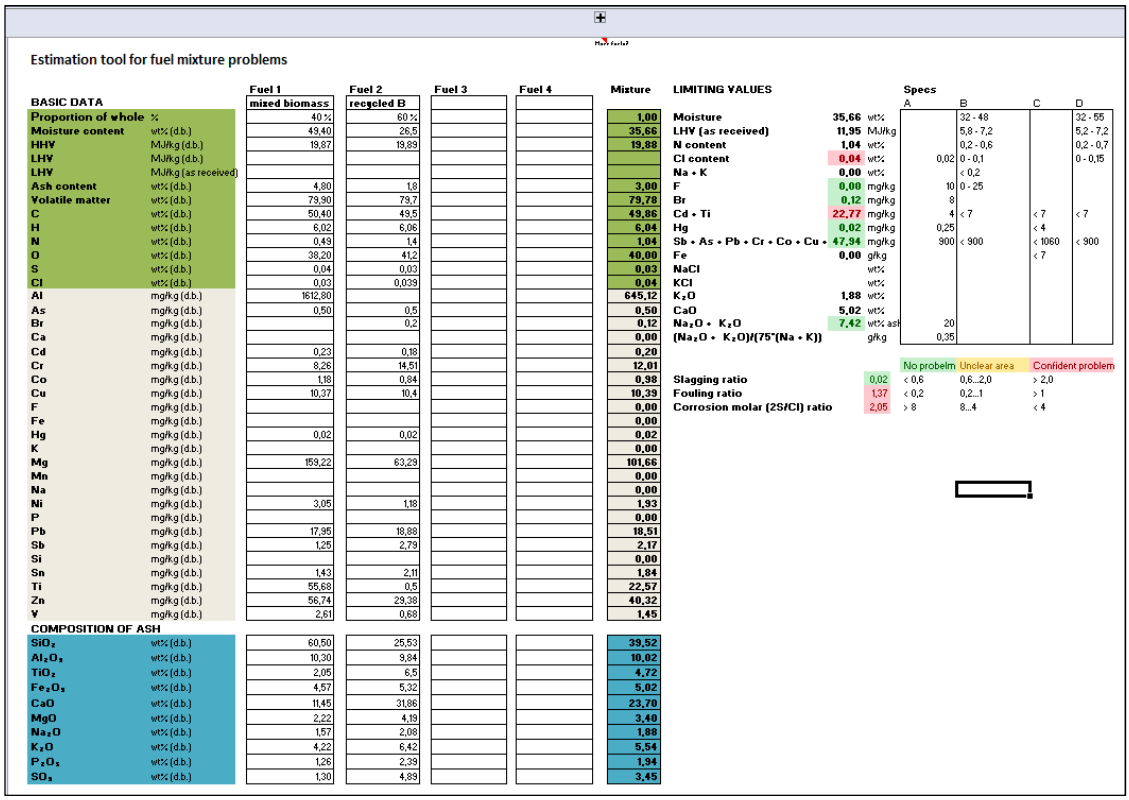
Molar mass for sulfur is 32,0655 g/mol and for chlorine it is 35,453 g/mol. Amount of substance of chlorine is calculated the same way and molar ratio is calculated

$$\frac{2\times n_S}{n_{Cl}} \qquad (16)$$

Slagging (12) and fouling (13) ratios are also used and their calculation method was introduced in Chapter 4.6.1. Those indicators in the tool use colors to represent the seriousness of problems. Red means a confident problem, yellow unclear area and green means no problem.

5.2 Model testing

The estimation tool is made as easy to use as possible. Everything is shown in the same page and it is easy and quick to see results. In Figure 5.1 is the overview of the tool.



Estimation tool for fuel mixture problems

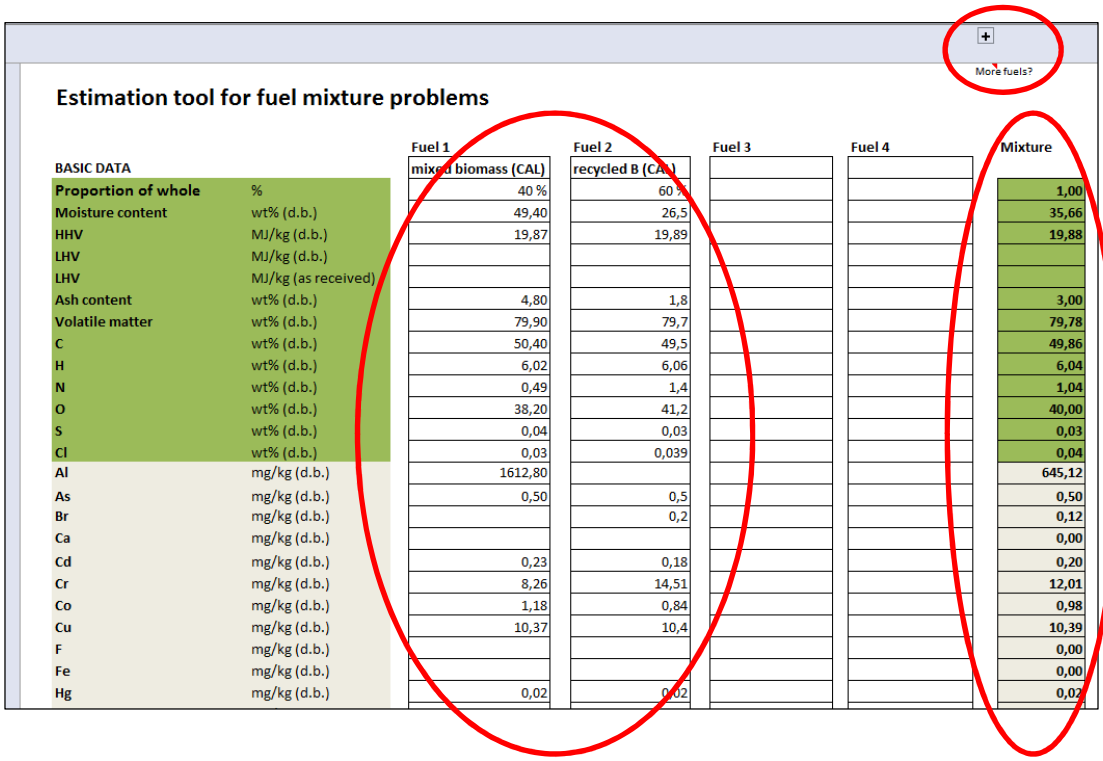
BASIC DATA		Fuel 1 mixed biomass	Fuel 2 recycled B	Fuel 3	Fuel 4	Mixture
Proportion of whole	%	40 %	60 %			1,00
Moisture content	wt% (d.b.)	49,40	26,5			35,66
HHV	MJ/kg (d.b.)	19,87	19,89			19,88
LHV	MJ/kg (d.b.)					
LHV	MJ/kg (as received)					
Ash content	wt% (d.b.)	4,80	1,8			3,00
Volatile matter	wt% (d.b.)	79,90	79,7			79,78
C	wt% (d.b.)	50,40	49,5			49,86
H	wt% (d.b.)	6,02	6,06			6,04
N	wt% (d.b.)	0,49	1,4			1,04
O	wt% (d.b.)	39,20	41,2			40,00
S	wt% (d.b.)	0,04	0,03			0,03
Cl	wt% (d.b.)	0,03	0,039			0,04
Al	mg/kg (d.b.)	1612,80				645,12
As	mg/kg (d.b.)	0,50	0,5			0,50
Br	mg/kg (d.b.)		0,2			0,12
Ca	mg/kg (d.b.)					0,00
Cd	mg/kg (d.b.)	0,23	0,18			0,20
Cr	mg/kg (d.b.)	8,26	14,51			12,01
Co	mg/kg (d.b.)	1,18	0,84			0,98
Cu	mg/kg (d.b.)	10,37	10,4			10,39
F	mg/kg (d.b.)					0,00
Fe	mg/kg (d.b.)					0,00
Hg	mg/kg (d.b.)	0,02	0,02			0,02
K	mg/kg (d.b.)					0,00
Mg	mg/kg (d.b.)	159,22	63,29			101,66
Mn	mg/kg (d.b.)					0,00
Na	mg/kg (d.b.)					0,00
Ni	mg/kg (d.b.)	3,05	1,18			1,93
P	mg/kg (d.b.)					0,00
Pb	mg/kg (d.b.)	17,95	18,88			18,51
Sb	mg/kg (d.b.)	1,25	2,79			2,17
Si	mg/kg (d.b.)					0,00
Sn	mg/kg (d.b.)	1,43	2,11			1,84
Ti	mg/kg (d.b.)	55,68	0,5			22,57
Zn	mg/kg (d.b.)	56,74	29,38			40,32
V	mg/kg (d.b.)	2,61	0,68			1,45
COMPOSITION OF ASH						
SiO_2	wt% (d.b.)	60,50	25,53			39,52
Al_2O_3	wt% (d.b.)	10,30	9,84			10,02
TiO_2	wt% (d.b.)	2,05	6,5			4,72
Fe_2O_3	wt% (d.b.)	4,57	5,32			5,02
CaO	wt% (d.b.)	11,45	31,86			23,70
MgO	wt% (d.b.)	2,22	4,19			3,40
Na_2O	wt% (d.b.)	1,57	2,08			1,88
K_2O	wt% (d.b.)	4,22	6,42			5,54
P_2O_5	wt% (d.b.)	1,26	2,39			1,94
SO_3	wt% (d.b.)	1,30	4,89			3,45

LIMITING VALUES			Specs A	B	C	D
Moisture	35,66	wt%		32 - 48		32 - 55
LHV (as received)	11,95	MJ/kg		5,8 - 7,2		5,2 - 7,2
N content	1,04	wt%		0,2 - 0,6		0,2 - 0,7
Cl content	0,04	wt%	0,02	0 - 0,1		0 - 0,15
Na + K	0,00	wt%		< 0,2		
F	0,00	mg/kg	10	0 - 25		
Br	0,12	mg/kg	8			
Cd + Ti	22,77	mg/kg	4	< 7	< 7	< 7
Hg	0,02	mg/kg	0,25		< 4	
Sb + As + Pb + Cr + Co + Cu +	47,94	mg/kg	900	< 900	< 1060	< 900
Fe	0,00	g/kg			< 7	
NaCl		wt%				
KCl		wt%				
K_2O	1,88	wt%				
CaO	5,02	wt%				
$Na_2O + K_2O$	7,42	wt% ash	20			
$(Na_2O + K_2O)/(75*(Na + K))$		g/kg	0,35			

		No problem	Unclear area	Confident problem
Slagging ratio	0,02	< 0,6	0,6...2,0	> 2,0
Fouling ratio	1,37	< 0,2	0,2...1	> 1
Corrosion molar (2S/Cl) ratio	2,05	> 8	8...4	< 4

Figure 5.1 *Estimation tool*

Fuel data is put separately for columns and if there are more fuel fractions, more columns can be added from the plus sign. The properties of the mixture are calculated on the right side. In Figure 5.2 can be seen closely where the input data is putted, from where the extra column can be added and where the tool calculates the output.



BASIC DATA		Fuel 1 mixed biomass (CAL)	Fuel 2 recycled B (CAL)	Fuel 3	Fuel 4	Mixture
Proportion of whole	%	40 %	60 %			1,00
Moisture content	wt% (d.b.)	49,40	26,5			35,66
HHV	MJ/kg (d.b.)	19,87	19,89			19,88
LHV	MJ/kg (d.b.)					
LHV	MJ/kg (as received)					
Ash content	wt% (d.b.)	4,80	1,8			3,00
Volatile matter	wt% (d.b.)	79,90	79,7			79,78
C	wt% (d.b.)	50,40	49,5			49,86
H	wt% (d.b.)	6,02	6,06			6,04
N	wt% (d.b.)	0,49	1,4			1,04
O	wt% (d.b.)	38,20	41,2			40,00
S	wt% (d.b.)	0,04	0,03			0,03
Cl	wt% (d.b.)	0,03	0,039			0,04
Al	mg/kg (d.b.)	1612,80				645,12
As	mg/kg (d.b.)	0,50	0,5			0,50
Br	mg/kg (d.b.)		0,2			0,12
Ca	mg/kg (d.b.)					0,00
Cd	mg/kg (d.b.)	0,23	0,18			0,20
Cr	mg/kg (d.b.)	8,26	14,51			12,01
Co	mg/kg (d.b.)	1,18	0,84			0,98
Cu	mg/kg (d.b.)	10,37	10,4			10,39
F	mg/kg (d.b.)					0,00
Fe	mg/kg (d.b.)					0,00
Hg	mg/kg (d.b.)	0,02	0,02			0,02

Figure 5.2 *Close overview of data input and output.*

Limiting values are calculated from the properties of the fuel mixture. Values are compared with specs. If the values are going to the critical side of the specifications, value goes red and when they remain under the critical side, it is green. In slagging, fouling and molar 2S/Cl ratios there are three different stages, so there is also moderate or unclear area, when the color is yellow.

LIMITING VALUES			Specs			
			A	B	C	D
Moisture	35,66	wt%		32 - 48		32 - 55
LHV (as received)	11,95	MJ/kg		5,8 - 7,2		5,2 - 7,2
N content	1,04	wt%		0,2 - 0,6		0,2 - 0,7
Cl content	0,04	wt%	0,02	0 - 0,1		0 - 0,15
Na + K	0,00	wt%		< 0,2		
F	0,00	mg/kg	10	0 - 25		
Br	0,12	mg/kg	8			
Cd + Ti	22,77	mg/kg	4	< 7	< 7	< 7
Hg	0,02	mg/kg	0,25		< 4	
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V	47,94	mg/kg	900	< 900	< 1060	< 900
Fe	0,00	g/kg			< 7	
NaCl		wt%				
KCl		wt%				
K_2O	1,88	wt%				
CaO	5,02	wt%				
$Na_2O + K_2O$	7,42	wt% ash	20			
$(Na_2O + K_2O)/(75*(Na + K))$		g/kg	0,35			

		No probelm	Unclear area	Confident problem
Slagging ratio	0,02	< 0,6	0,6...2,0	> 2,0
Fouling ratio	1,37	< 0,2	0,2...1	> 1
Corrosion molar (2S/Cl) ratio	2,05	> 8	8...4	< 4

Figure 5.3 *Limiting values are highlighted with traffic light.*

When the tool was tested, it was found to provide similar results than empirical data. Often the calculated values were, however, in unclear area of limits, when the emergence of the problem could not be estimated with certainty. In these cases, the emergence of the problem depends on conditions in the boiler during combustion. It can therefore be said that, problems cannot be reliably estimated only estimating with this model.

6 CORRELATION BETWEEN FUELS AND FAILURES

In this section are studied four different BFB boilers in different power plants and the effects of the fuels on the problems of the boilers. These four boilers are in Europe and in the Table 6.1 shows general information about them. When in future a power plant is mentioned, it means only the boiler that can be seen in the next table.

Table 6.1 *General information about the power plants*

Power plant	Location	Boiler	Start-up	Fuels
A	UK	90 MW_{th}, 510 °C/90 bar	2009	• Demolition wood • Bark • Effluent sludge • Roundwood • Sawmill residues • Forest residues • DIP sludge and rejects • Natural gas
B	France	82 MW_{th}, 485 °C/83 bar	2007	• DIP and effluent sludge • DIP rejects • Wood • Gas
C	Finland	120 MW_{th}, 540 °C/120 bar	2006	• Bark • Forest residues • Peat • Sludge • RDF
D	UK	83 MW_{th}, 485 °C/82 bar	2008	• Sludge • Forest residues • Sawmill residues • Waste wood • RDF

The study consists of data collection and analysis. The aim is to find the evidence of the existing conformity to compare the situations of boilers and to find correlations between fuels and the factors which cause problems. Section 6.1 describes the data collation, Section 6.2 processing of the data and the Section 6.3 will focus on the results.

6.1 Data collation

Every power plant has collected their own data in their own way. Systematic data collation has not been done before, so all the data wasn't congruent with each other. Some fuel analyses had been collected in previous years, but more detailed information was wanted to obtain more accurate results. Each of four power plants was asked the following issues form start-up date:

- **Monthly fuel reporting** (different biofuels separately, moisture contents, heating values, tons, MWh).
- **Inspection reports, revisions reports** (reports about boiler failures, what has happened, what have made those failures, what have done/will be doing about to fix that problem.)
- **Fuel analyses**

The data was difficult to obtain and the quality of the data also varied, as each power plant has its own way to report the above issues. Comparability is challenging due to varied data. Also the fuel compositions and properties can vary in different power plants and different country.

6.2 Processing of the data

After the data collection the analysis was started. First the data was modified as similar as possible due to mutual comparability. After that the search for the cause-effect relationships was started with the variety of the graphical presentation with Microsoft Excel 2010 software. The most important characteristics, which were took into account was fuel, moisture content, ash content, Cl content and some limiting values for example the molar sulfur/chlorine-ratio. The identified problems were also added in graphs.

Different fuel fractions impact on the overall properties of the fuel mixture is compared with the figure, where the x-axis shows fuel fractions as a percentage of the whole fuel mixture and the y-axis of the selected feature (moisture content, ash content, chlorine content) of the whole mixture. Dots were added each month of the measured value and for this set of points was taken a linear trend line. This figure told the fuel fractions impact on the overall fuel mix of the property. If a linear trend is descending, the effect of the fuel fraction on fuel mixture characteristic is decreasing. If a linear trend is ascending, the effect is growing. These results were compared with the characteristics of the fuel fractions.

Correlations between the used fuels and the problems are tried to find with figures, whose x-axis was time. In used fuels and detect changes in them were put to these graphs. The progression of properties over the same period was also added to compare them with used fuel, as well as limiting factors. The same graph also contains problems occurring at these times. There can also look for cause and effect relationships by comparing the use of fuel and fuel mixture properties.

One aim was to collect the properties of the fuels and estimate the typical values for fuel fractions for each power plant. Results are introduced in the next chapter.

6.3 Results

Results chapter is divided in three parts: the values of typical fuel, correlation figures and used fuels and failures. Figures 6.1, 6.2, 6.3 and 6.4 introduce the used fuels for every power plant. Values are only the used fuels in BFB-boiler. All used fuel data are calculated with MWh.

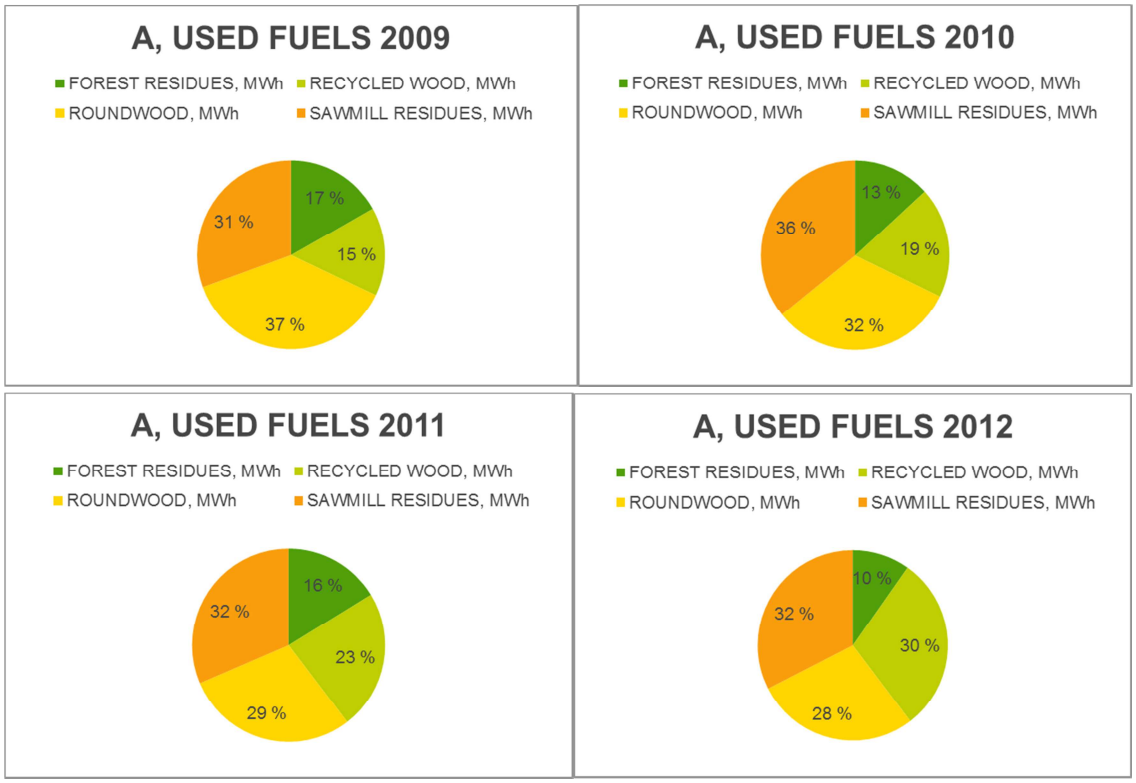


Figure 6.1 *Used fuels for power plant A. Year 2009 is from May to December and year 2012 from January to May.*

In power plant A, amount of recycled wood fuel is increasing, which also describes problems in the boiler.

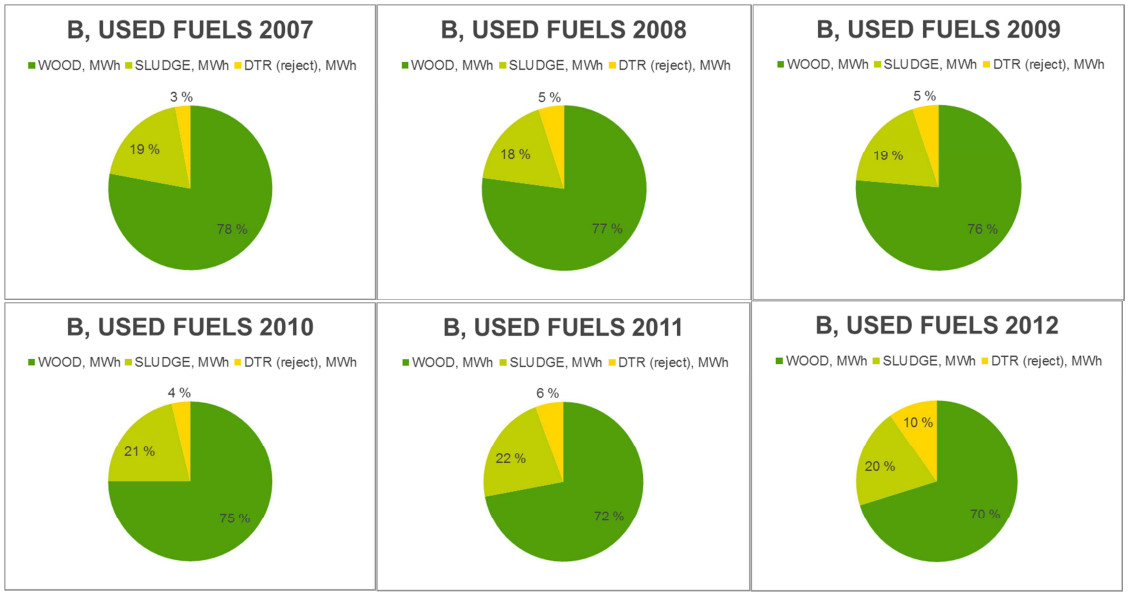


Figure 6.2 *Used fuels for power plant B. Year 2012 is from January to July.*

In power plant B, rejects are also increasing, but not as much as power plant A. Sludge content can be increasing ash content, but values of ash content are not available.

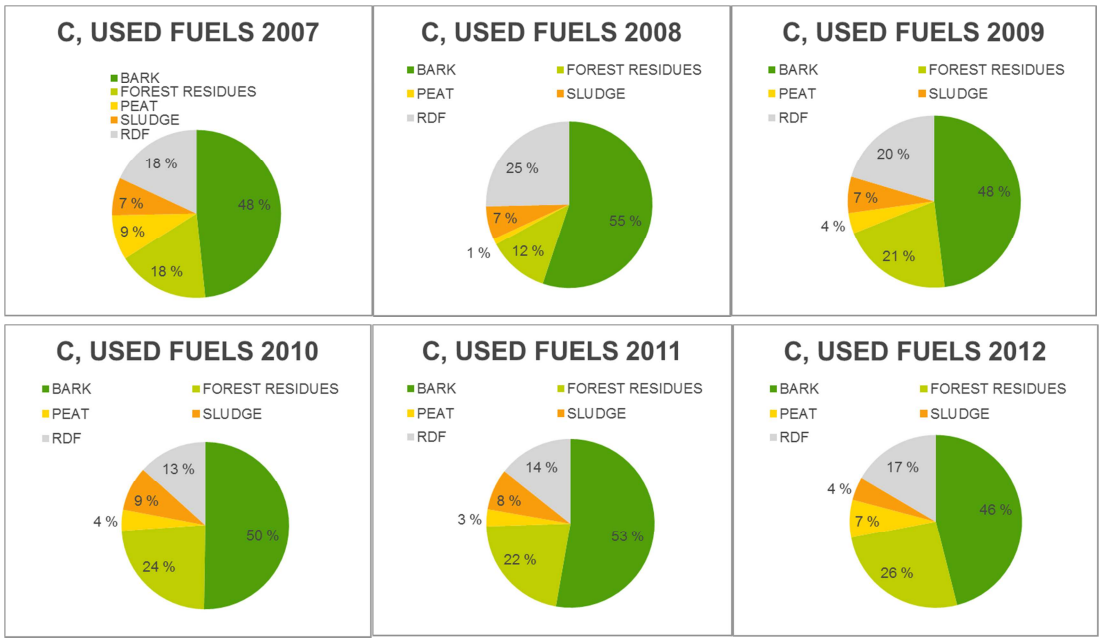


Figure 6.3 *Used fuels for power plant C. Year 2012 is from January to May.*

In power plant C, amount of RDF is quite smooth. Bark has always been the main fuel.

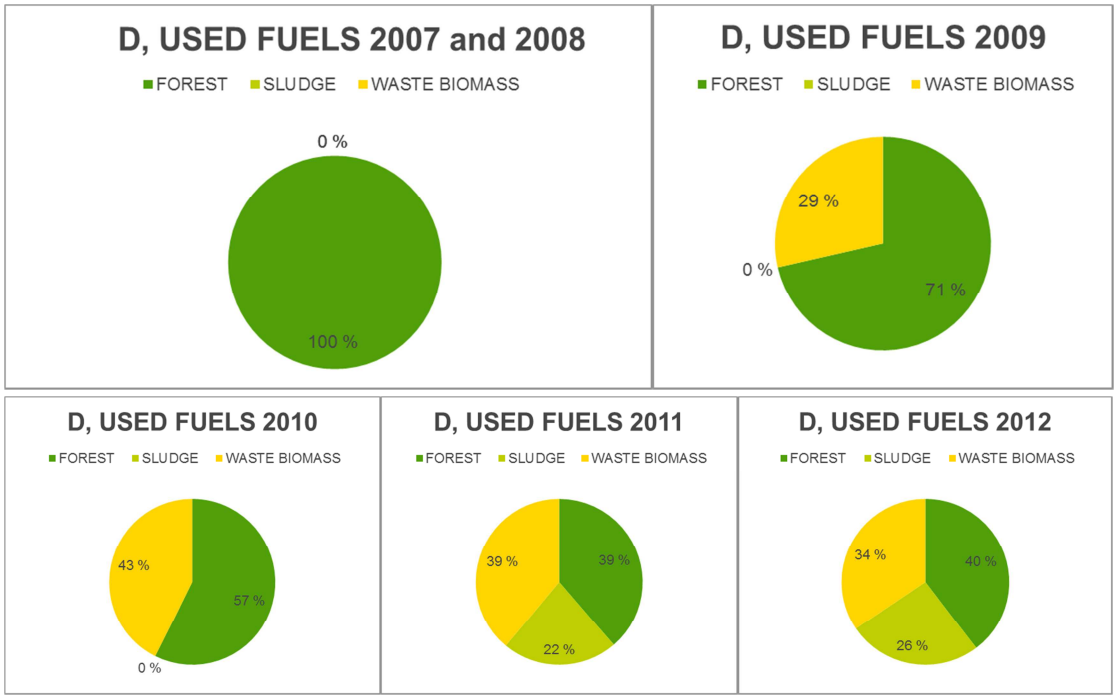


Figure 6.4 *Used fuels for power plant D. Year 2012 is from January to May.*

In power plant D, waste fuels came to the fuel palette in 2009. In the years 2011 and 2012 the fuel palette has been quite the same.

6.3.1 Values of typical fuel

Here are collected typical values for fuel fractions of every power plant. In the next tables are also compared the same fuel fractions of every power plant. Here is only shown moisture content, ash content, calorific values and ultimate analysis of fuels. Every power plant does not have fuel analyses for every fuel fraction, but everything available is introduced. Fuel analyses data was also very varied. If there are minimum and maximum values, the year value is an average for the whole year. Exceeded values are also marked compared with specification values of power plant. Table 5.1 has specification values for the fuel mixture, but if there are specs values for every fuel fraction, values are mentioned in the caption.

Table 6.2 *Typical values for wood-based fuels*

WOOD	**A**				**B**					
	Pallet			**Sawmill residues**	**Wood**		**Pallet**	**Forest residues**		
	2011	**min**	**max**	**2011**	**2011**	**2008**	**2008**	**2008**	**2007**	**2006**
Moisture, %	26,82	18,70	41,00	59,60	20,3	22,56	14,6	38,5	-	20,4
Ash (w-%, d.b.)	0,78	0,40	1,30	0,10	3,7	1,23	1,7	0,3	-	1,7
HHV (MJ/kg, d.b.)	20,13	19,31	20,55	20,24	19,67	20,45	20,43	20,51	-	-
LHV (MJ/kg, ar)	12,96	10,31	14,86	6,22	12,09	14,25	15,95	10,86	-	-
C (w-%, d.b.)	51,15	50,20	53,80	49,90	49,1	49,93	49,6	50,6	45,2667	41,72
H (w-%, d.b.)	6,22	5,75	6,50	5,70	5,9	6,13	6,15	6,1	5,433	5,91
S (w-%, d.b.)	0,05	0,01	0,20	0,01	0,065	0,036	0,045	0,02	0,1513	5,74
Cl (w-%, d.b.)	0,03	0,01	0,12	0,01	0,042	0,077	0,11	0,008	0,3223	157
N (w-%, d.b.)	0,25	0,05	0,48	0,27	0,82	0,7	0,955	0,19	1,1233	3,28
O (w-%, d.b.)	41,49	38,70	42,80	44,00	40,3	-	-	-	-	40,09

The moisture contents of wood-based fuels are quite varied, but higher heating values are almost the same.

Table 6.3 *Typical values for waste wood, A: Moisture 20,2%, ash 1,1%, LHV (ar) 19,07 MJ/kg, C 50,4%, H 5,9%, S 0,03%, Cl 0,075%, N 0,8%, O 41,7%*

WASTE WOOD	A						C			D
	2012	min	max	2011	min	max	2010	min	max	2011
Moisture, %	23,17	18,8	29,9	24,81	18,5	31,5	32,89	20,6	42,7	19,65
Ash (w-%, d.b.)	2,74	1,5	9,0	3,09	0,7	8,1	2,133	0,7	3,4	1,8
HHV (MJ/kg, d.b.)	19,57	18,79	19,99	19,66	16,93	20,46	21,23	20	25,42	19,65
LHV (MJ/kg, ar)	13,48	11,6	14,3	13,17	11,5	14,58	14,42	9,98	22,68	13,34
C (w-%, d.b.)	49,92	48,2	51,9	49,45	45,9	51,1	51,27	49,1	56,2	50,1
H (w-%, d.b.)	5,88	4,75	6,38	6,08	5,42	7,08	6,617	6,2	8,0	6,06
S (w-%, d.b.)	0,05	0,02	0,08	0,07	0,01	0,37	0,04	0,02	0,06	0,09
Cl (w-%, d.b.)	0,13	0,03	0,24	0,04	0,01	0,18	0,047	0,003	0,12	0,01
N (w-%, d.b.)	1,42	1,01	1,97	1,51	0,55	2,17	0,395	0,18	0,67	1,93
O (w-%, d.b.)	39,79	35,4	41,6	39,77	35,7	44,7	-	-	-	40

Chlorine and ash contents of the waste wood are high in every plant. That can be expounding on impurities in fuels. Moisture content can also be high. It can be seen that variation of the values of properties is also great in waste wood.

Table 6.4 *Typical values for compost and DIP rejects and RDF*

Waste and rejects	B						C			
	Compost rejects		DIP rejects				RDF			Label waste
	2006	2008	2008	min	max	2011	2010	min	max	2010
Moisture, %	23,4	31,933	27,48	4,4	51,9	67,3	22,50	9,6	32,4	4,4
Ash (w-%, d.b.)	8,1	12,600	8,9	5,2	12,5	15,6	12,89	7,1	22,1	2,8
HHV (MJ/kg, d.b.)	-	18,173	35,02	38,21	32,58	31,83	22,42	17,88	26,93	29,84
LHV (MJ/kg, ar)	-	10,790	16,79	7,12	21,35	-	17,6	10,85	26,36	26,39
C (w-%, d.b.)	36,52	45,267	68,64	64,4	73,9	62,2	50,73	41,6	57,2	61,7
H (w-%, d.b.)	5,09	5,433	10,24	9,3	11,5	9,3	7,2	6,0	8,9	9,9
S (w-%, d.b.)	0,68	0,143	0,09	0,03	0,17	0,052	0,19	0,09	0,37	0,02
Cl (w-%, d.b.)	0,61	0,347	2,98	0,48	4,0	1,6	0,32	0,075	0,46	0,016
N (w-%, d.b.)	0,65	1,123	0,24	0,21	0,31	0,11	0,57	0,16	1,02	0,18
O (w-%, d.b.)	39,06		-	-	-	13,7	-	-	-	-

For different waste fuels, properties are quite varied. Ash and chlorine content are very high.

Table 6.5 *Typical values for sludge, A: Moisture 40%, C 39,20%, H 5,2%, S 0,13%, Cl 0,04%, N 0,13%, O 37,6%*

SLUDGE	A			B	C
	2011	min	max	2007-2008	2010
Moisture, %	55,75	52,10	59,40		75,2
Ash (w-%, d.b.)	37,40	27,30	47,50		
HHV (MJ/kg, d.b.)	12,52	10,36	14,67		13,81
LHV (MJ/kg, ar)	3,7	3,31	4,1		1,36
C (w-%, d.b.)	35,15	31,40	38,90	23	
H (w-%, d.b.)	4,16	3,65	4,66	2,65	
S (w-%, d.b.)	0,05	0,04	0,05	0,056	0,58
Cl (w-%, d.b.)	0,04	0,04	0,04	0,0198	0,1
N (w-%, d.b.)	0,19	0,10	0,27	0,39	
O (w-%, d.b.)	23,05	17,10	29,00		

Table 6.6 shows typical values for all biomass fuels, which go to the boiler.

Table 6.6 *Typical values for biomass fuels, A: Cl 0,02%*

BIOMASS	A						D					
	2012	min	max	2011	min	max	2011	min	max	2012	min	max
Moisture, %	55,04	50,7	59,3	54,92	46,20	66,80	35,31	31,2	42	41	36,40	54,60
Ash (w-%, d.b.)	3,83	2,80	5,0	4,09	1,40	8,80	29,46	5,5	52,4	23,74	2,96	42,30
HHV (MJ/kg, d.b.)	19,28	17,94	19,63	19,71	18,65	20,73	14,66	10,1	18,86	14,6	9,96	19,62
LHV (MJ/kg, ar)	6,76	5,91	7,65	6,59	4,50	8,85	8,09	4,45	10,8	8,94	5,81	13,72
C (w-%, d.b.)	49,89	48,50	51,30	49,83	47,30	54,00	39,3	30,9	46,2	39,1	26,72	49,60
H (w-%, d.b.)	5,76	5,26	6,09	6,0	4,80	6,80	4,24	2,7	2,7	4,47	3,12	5,68
S (w-%, d.b.)	0,04	0,01	0,10	0,04	0,01	0,14	0,1	0,03	0,43	0,06	0,03	0,13
Cl (w-%, d.b.)	0,07	0,03	0,13	0,02	0,00	0,09	0,11	0,02	0,33	0,09	0,04	0,17
N (w-%, d.b.)	0,66	0,19	1,22	0,74	0,23	1,87	0,73	0,17	1,3	0,8	0,37	1,13
O (w-%, d.b.)	39,73	37,50	41,40	39,24	34,10	43,60	26,04	13,5	41,4	27,6	17,60	40,80

Biomass in A includes: Forest wood, recycled wood, roundwood and sawmill residues. Biomass in D includes: Deinking sludge, bio-sludge, primary effluent sludge, forestry wood, clean recycled wood and dirty recycled wood

The high ash content of the case D expounded on sludge, because its ash content can be more than 40%.

6.3.2 Correlation figures

The best available data came from power plant A. That is the reference and with that data was analyze made. The data of power plant D was moderately good, so comparison can be made with A and D. With other data (B and C), comparison can be made only with used fuels, failures and moisture contents.

Figure 6.5 shows correlation curves for plant A forest and recycled wood fuels and plant D wood and waste biomass fuels.

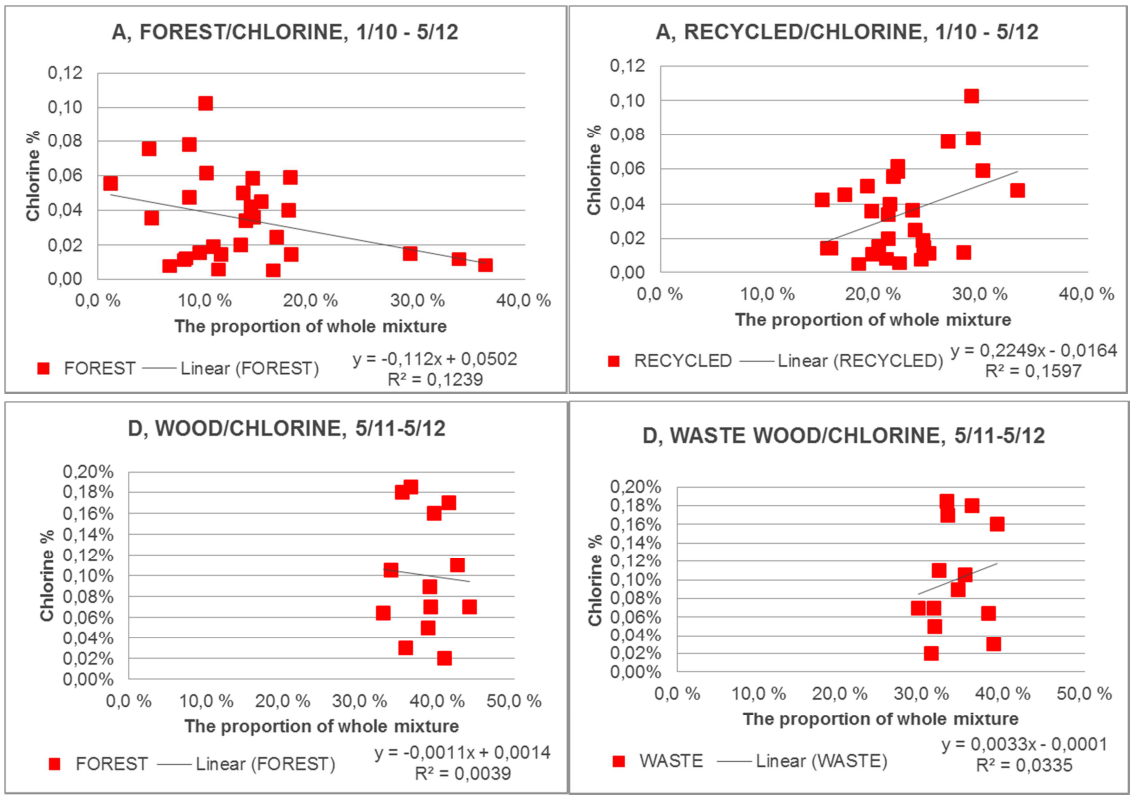


Figure 6.5 *Correlations between the proportion of fuel fractions of fuel mixture and chlorine content of the whole mixture.*

It can be seen that recycled and waste wood increase the chlorine content of the fuel mixture. The reason is the impurities of waste wood, which have the high chlorine content. Comparing Tables 6.2 and 6.3 can be seen that chlorine content of waste fuels is higher. Forest residues and other normal wood fuels do not increase chlorine content, because chlorine content of the wood is not that high. Correlations between wood and recycled fuels and ash contents are n the next Figure 6.6.

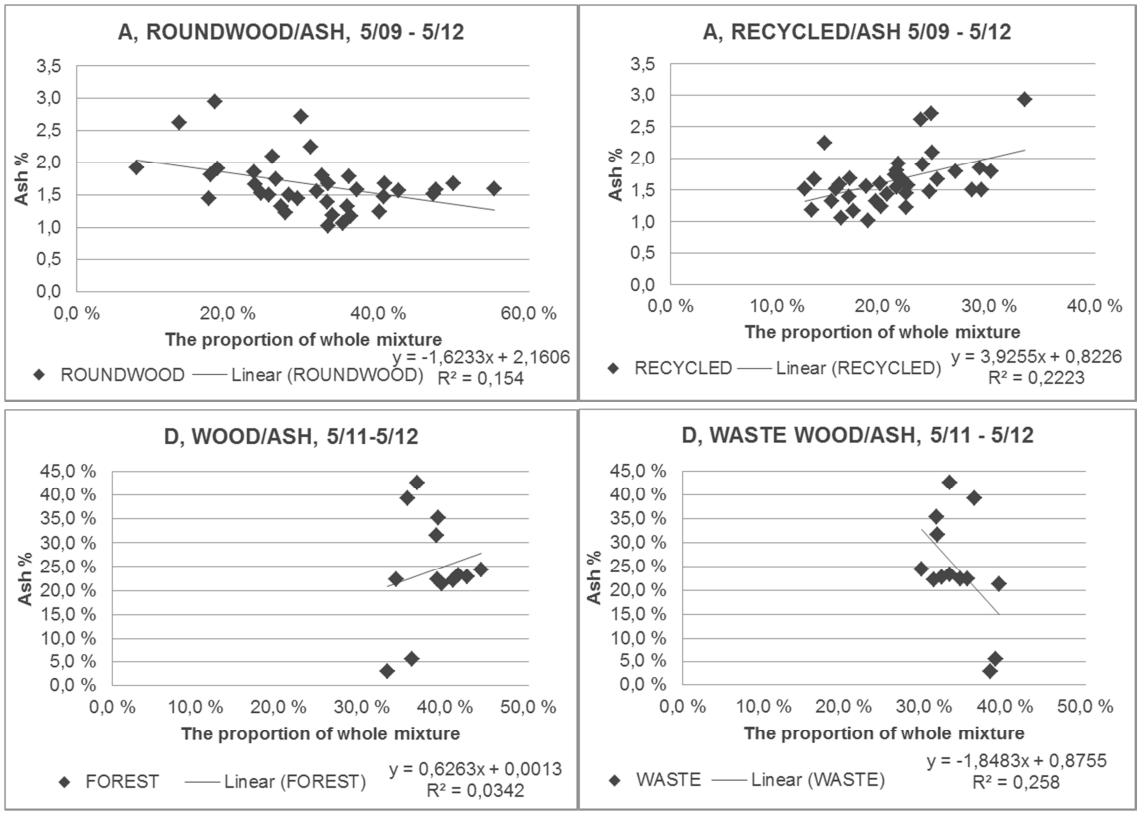


Figure 6.6 *Correlations between the proportion of fuel fractions of fuel mixture and ash content of the whole mixture.*

Correlations in power plant A are obvious with the same explanations as in the chlorine content case. In power plant D the correlations have different trend. One explanation can be ash content in the waste fuels, which in power plant D is lower than in power plant A. That can be seen in typical fuel values. There are not any values for wood fuels for power plant D, but in biomass table 6.5 can be found that ash contents can be very varied. It has to be taken into account that in biomass fuel can also include sludge.

6.3.3 Used fuels and failures

Next figures show used fuels, failures and some property, which is found out expounded on the reasons for the problems. Bigger and exact figures can be found in Appendixes 1, 2, 3 and 4. Appendix 5 contains used fuels and failures for power plants B and C.

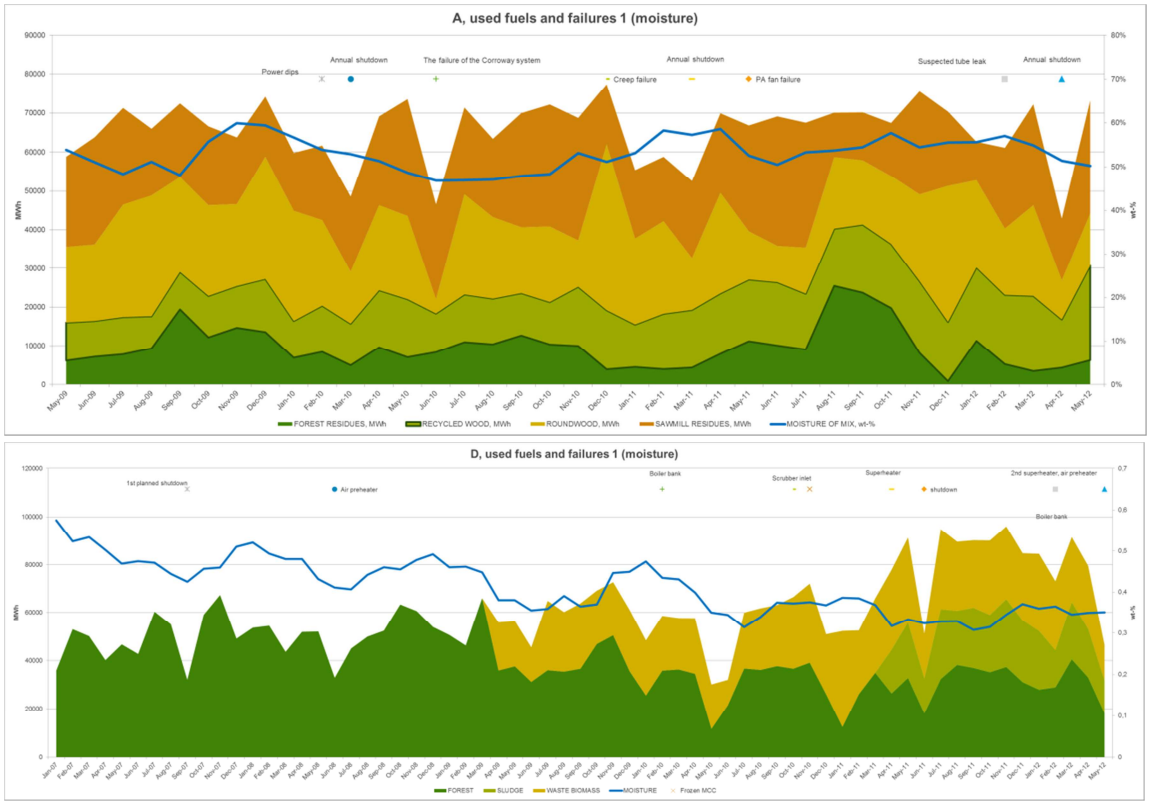


Figure 6.7 *Used fuels and the moisture content of the whole mixture for power plants A and D. Appendix 1.*

The figure of power plants A and D show that forest residues high moisture content increases the moisture content of the whole mixture. In the moisture content curve of D can be seen the seasons change: in winter wood-based fuels are more moisture than in summer. In winter rain and snow are increasing moisture content. The trend of the moisture content curve is descending and that is expounded on waste fuels, which are in power plant D quite dry, as can be seen in Table 6.3. Sludge stops descending, because it has high moisture content.

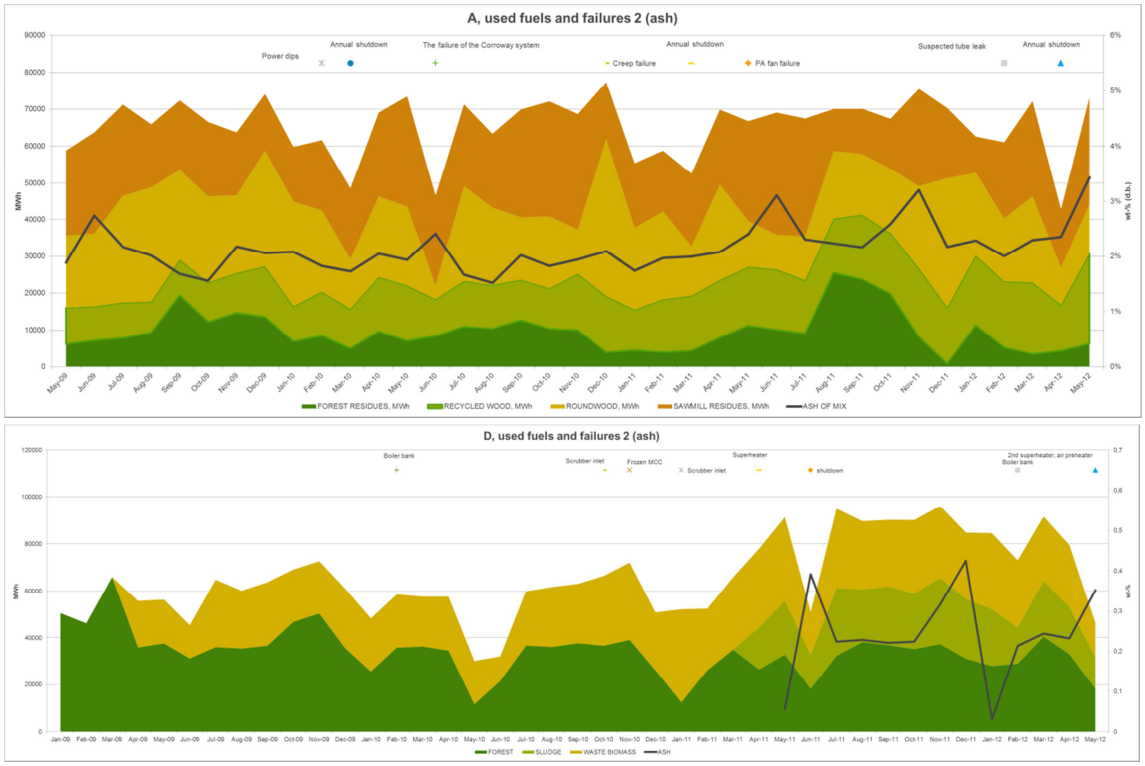


Figure 6.8 *Used fuels and the ash content of the whole mixture for power plants A and D. Appendix 2.*

In figure D two points (May 2011 and Jan 2012) are possible errors of measuring, because values vary much. Other expounds on that could be that in the measuring there was not that much sludge in the fuel mixture. The sludge curve is a little bit descending, but not much.

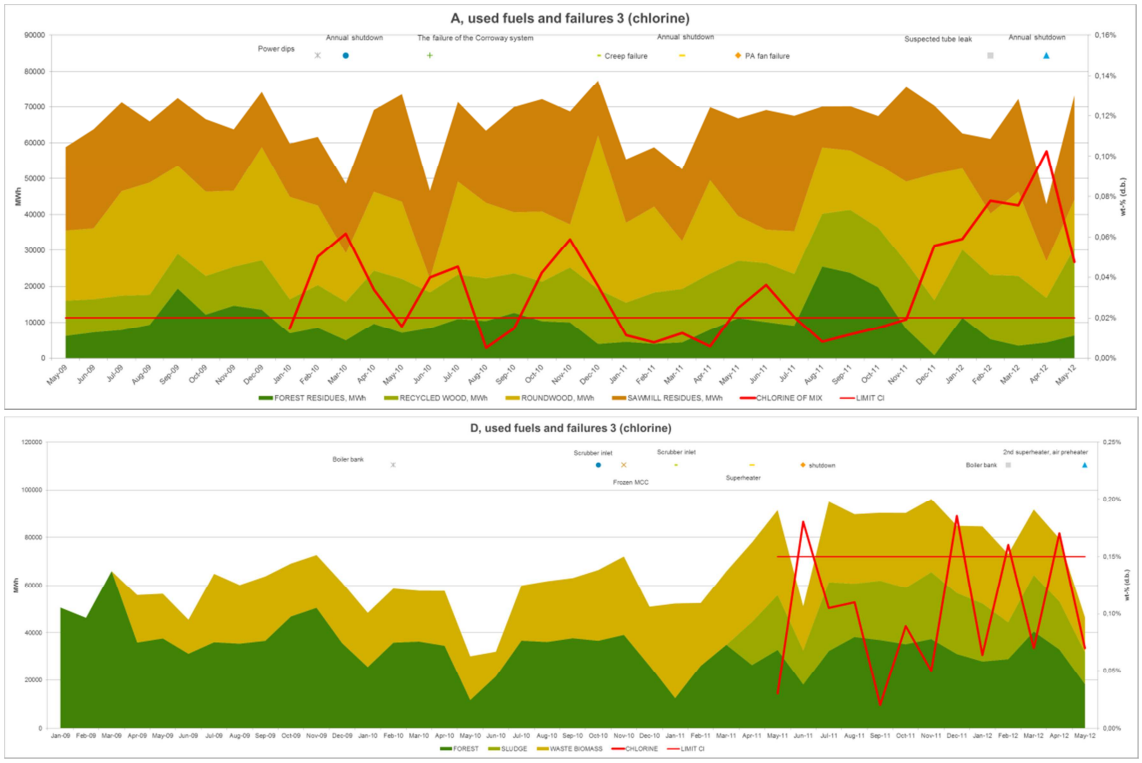


Figure 6.9 *Used fuels and the chlorine content of the whole mixture for power plants A and D. Appendix 3.*

In case A chlorine content crosses the limit value very often, which is quite alarming. In this case in power plant A is used a system, which prevents corrosion, but it does not show in the properties of fuel. It will be shown in flue gas analyses. In case D, the limit of chlorine content is quite high, because the boiler is designed for the sludge. Chlorine content keeps very well under the limit value.

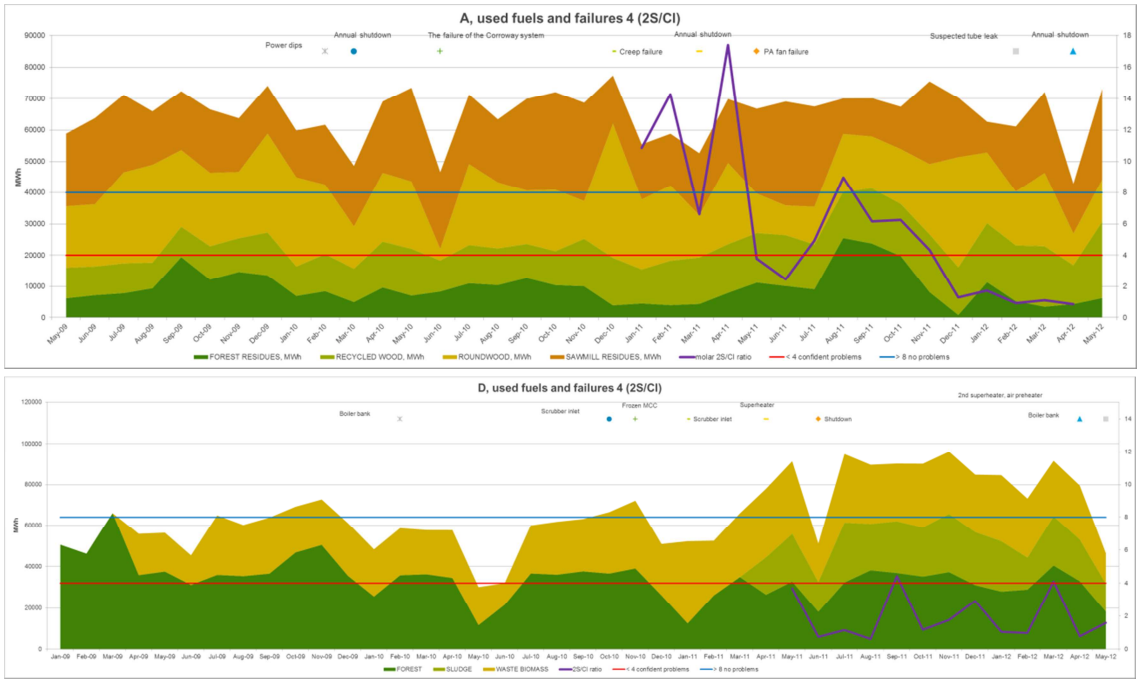


Figure 6.10 *Used fuels and the molar 2S/Cl ratio of the whole mixture for power plants A and D. Appendix 4.*

In figures, the blue line is telling low corrosion risk level, which is 8. Between 4 and 8 is the moderate the level of corrosion and red line under it tells the high corrosion risk level. In case A, the molar 2S/Cl ratio is at low and moderate level, but then goes under 4. The same trend can be seen from Figure 6.9. In case D, the ratio is almost under 4 all the time. That expounds on quite high corrosion content and also low sulfur content, but that is must be inspect better.

7 CONCLUSIONS

The EU requires (Directive 2009/28/EC) to raise the share of renewable energy in final energy consumption by 2020. This challenging aim is planned to be reached by promoting the use of biomass-based energy, wind power, biofuels as well as increasing the use of heat pumps. Wood-based biomass fuels make a major contribution to this goal.

Using biomass fuels, the composition of fuels should be carefully considered. The elementary composition, lower heating value, moisture content and the ultimate analysis of the fuels must be known and the composition and properties of ash must be studied. The properties of ash cannot be predicted based only on the composition of fuel. Values must be studied separately before and after combustion. To mix different biomass fuel fractions, one should definitely know the properties of individual fuels, as well as the properties of the mixture, mixture ratio and the properties of the ash. Suggestive estimation of the problems in the boiler can be made with this information. It has to be taken into account that all analyses of fuels and ashes are very suggestive and quite small amount of melting ash can cause problems. Impurities are easily collected to bed sand, so changing bed sand often helps to avoid the problems in the boiler.

Combustion of biomass requires many technical matters in boiler, especially in high-quality materials that are resistant to corrosion, erosion and high temperatures. Choosing right material for the high temperature heating surfaces is also an optimization problem. When the selections are made the fuel palette has to be taken into account. It is not easy to optimize because the fuel palette can change later. When the new fuel fractions are coming to the palette, they have to be tested with chosen material and study, if the fuel fractions are proper for the material or if materials should be changed.

The problems of combustion of biomass are affecting the power plants investment, operating and maintenance costs. To prevent the problems must expensive process, structural and material solutions, as well as equipment purchases be made. Use of various additives increases the operating costs as well as consumption of bed sand. Due to these problems, the maintenance costs of the plant rise. It forces to use varying maintenance procedures more often. In some situations it is more advantageous to accept a number of problems that have a clear solution than change fuels to cleaner, but more expensive ones. The plant must assess the types of problems that are acceptable and those that are not.

The result of the analysis showed that systematic gathering of fuel data plays a key role in problem detection. In order to detect problems, must fractions of fuel and the mixture be well-known. The estimation tool of the properties of fuel mixture and the problems will help this issue. It estimates the properties of the fuel mixture with given

limit values. The fuel data from the power plants was plotted in graphs. It supports the data from literature and flue analyses from the power plant. The graphs did not find clear correlations between the used fuels and the problems. The problems are complex due to many different reasons. The fuel data from the power plants was partially incomplete and varying. Deep analysis was challenging to make.

As further actions I propose a systematic fuel data collection on a monthly basis from every power plant. It is also important to collect data continuously from those power plants, which do not have many problems, as a reference. Ideal situation is a real-time measurement system in every power plant, but systems are very expensive. However, the survey of potential of real-time measurement systems should be made. Statistical investigations can be made and relations between fuels and the failures found after at least nearly complete fuel data is collected.

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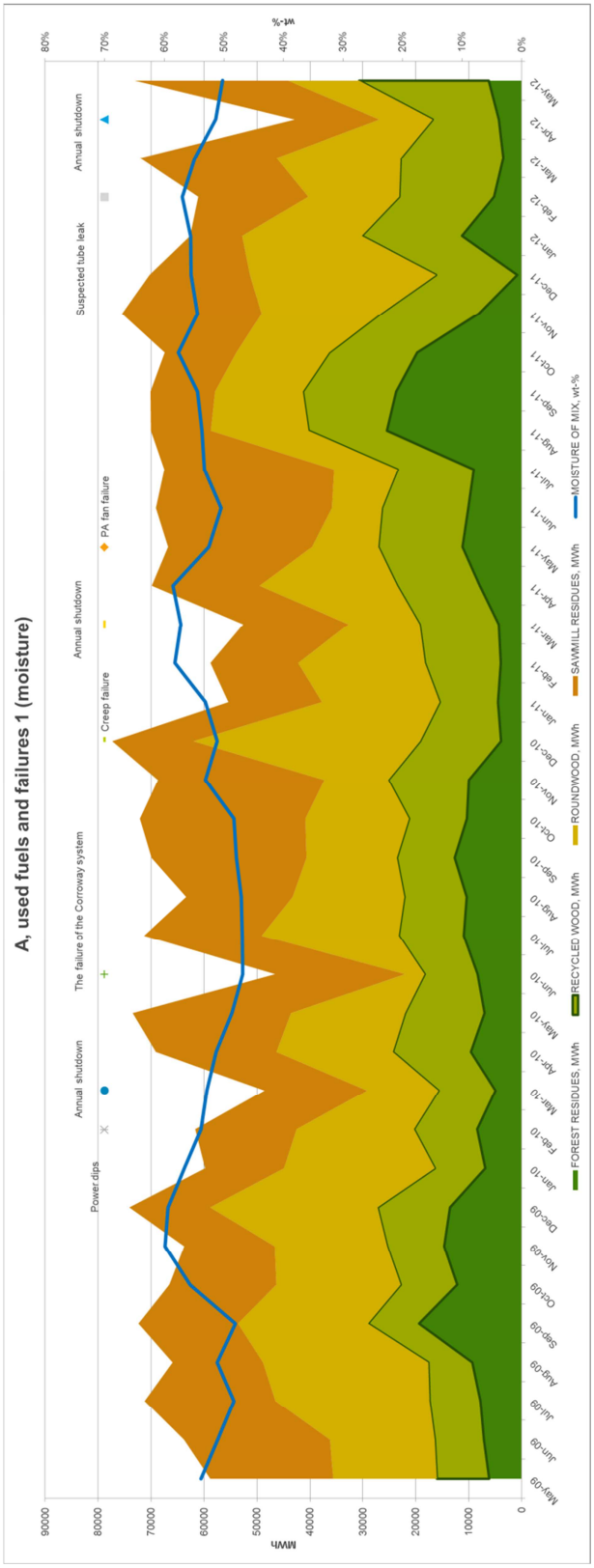
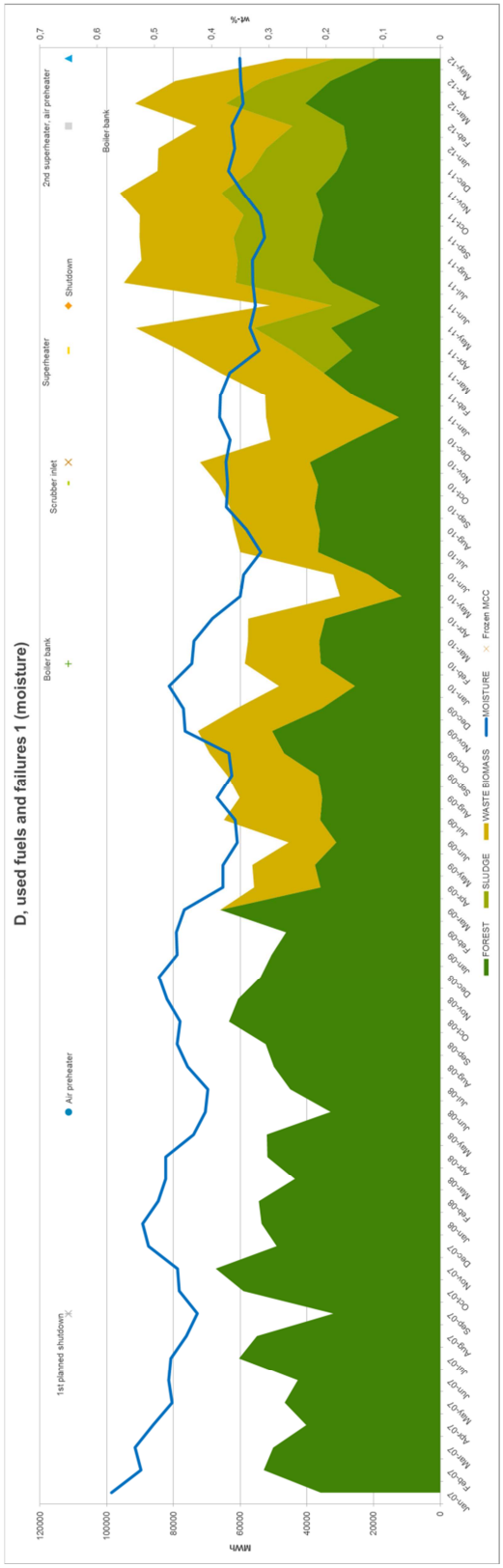
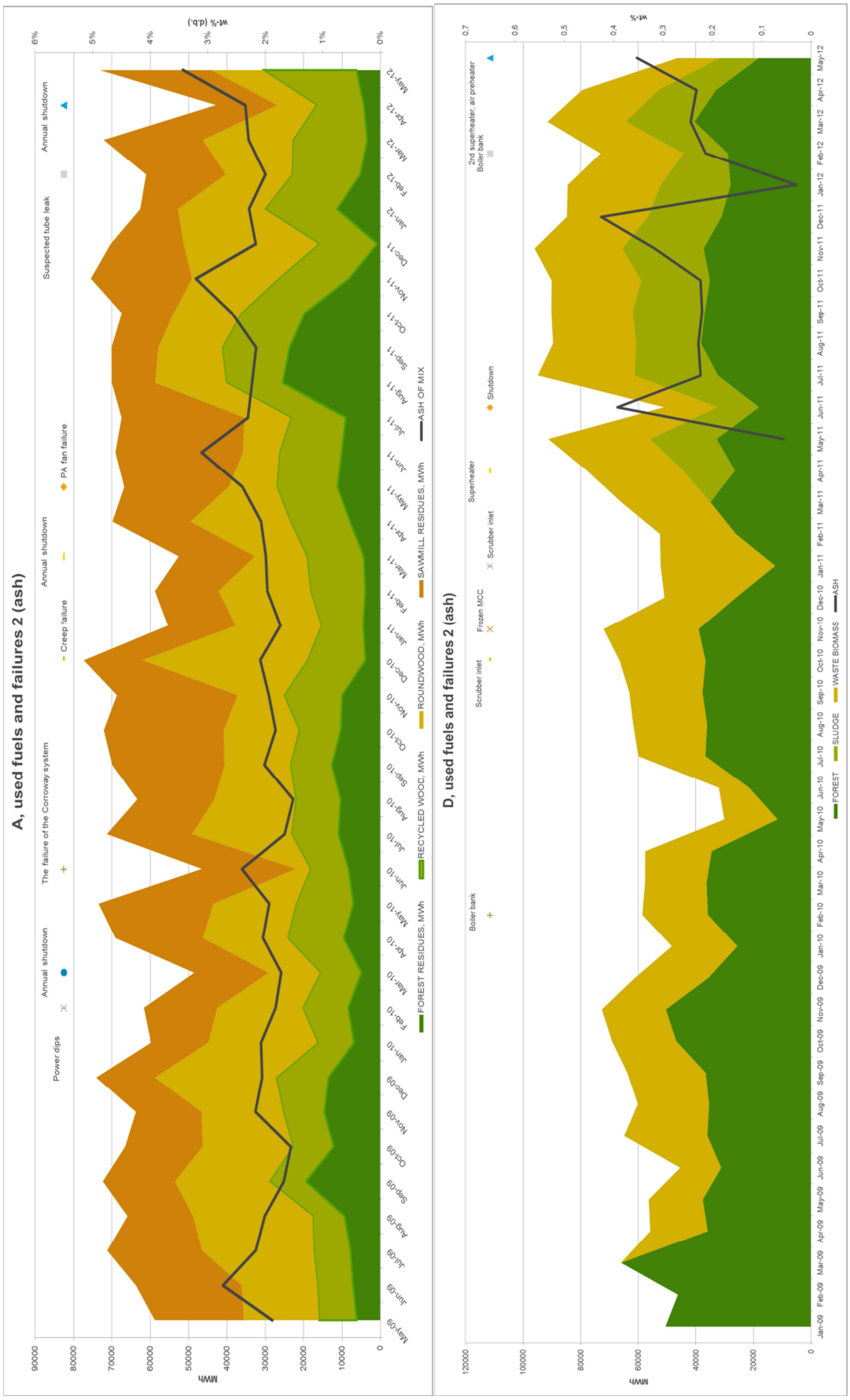
APPENDIX 1: USED FUELS AND THE MOISTURE CONTENT OF THE WHOLE MIXTURE FOR POWER PLANTS A AND D

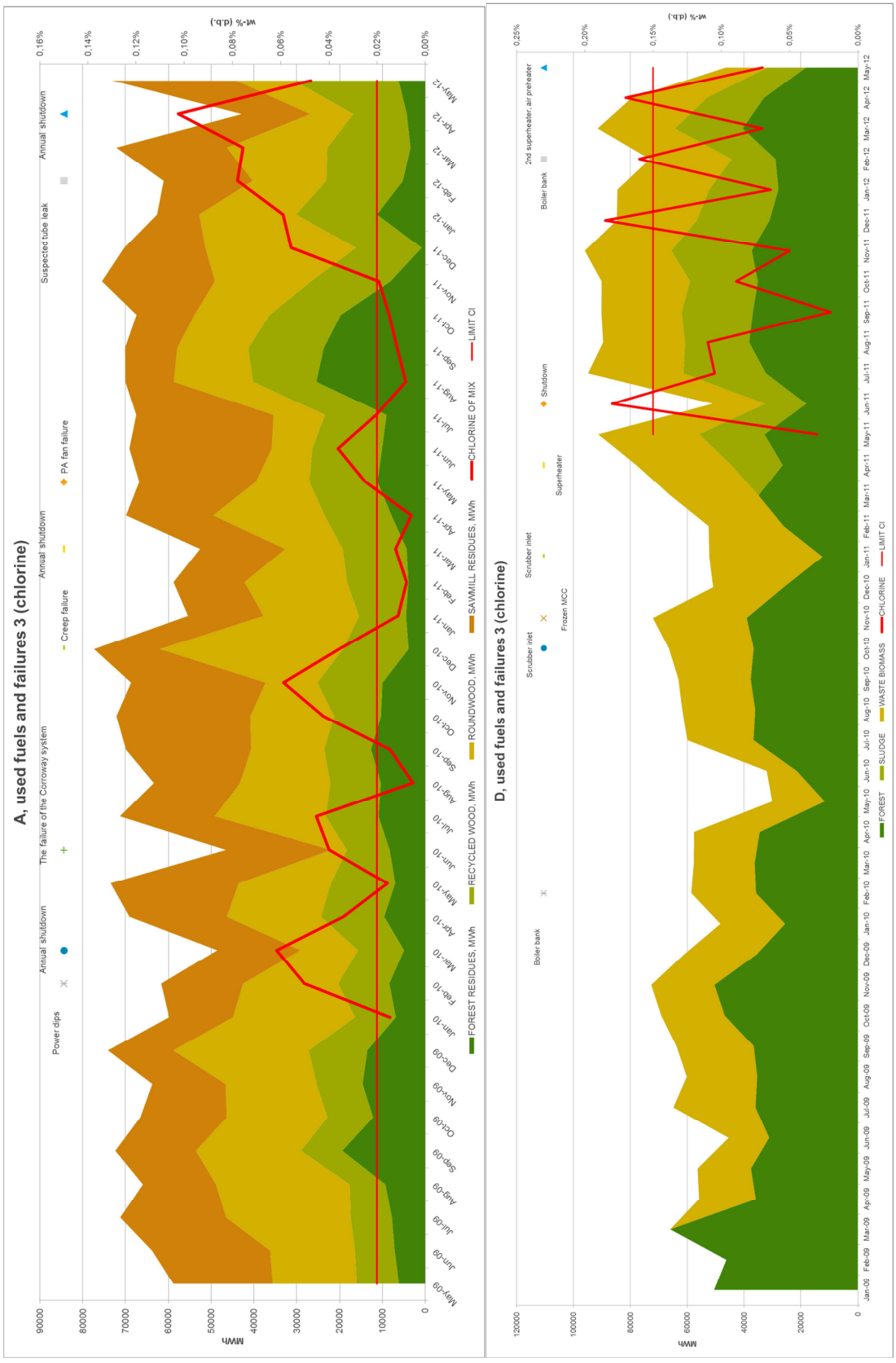




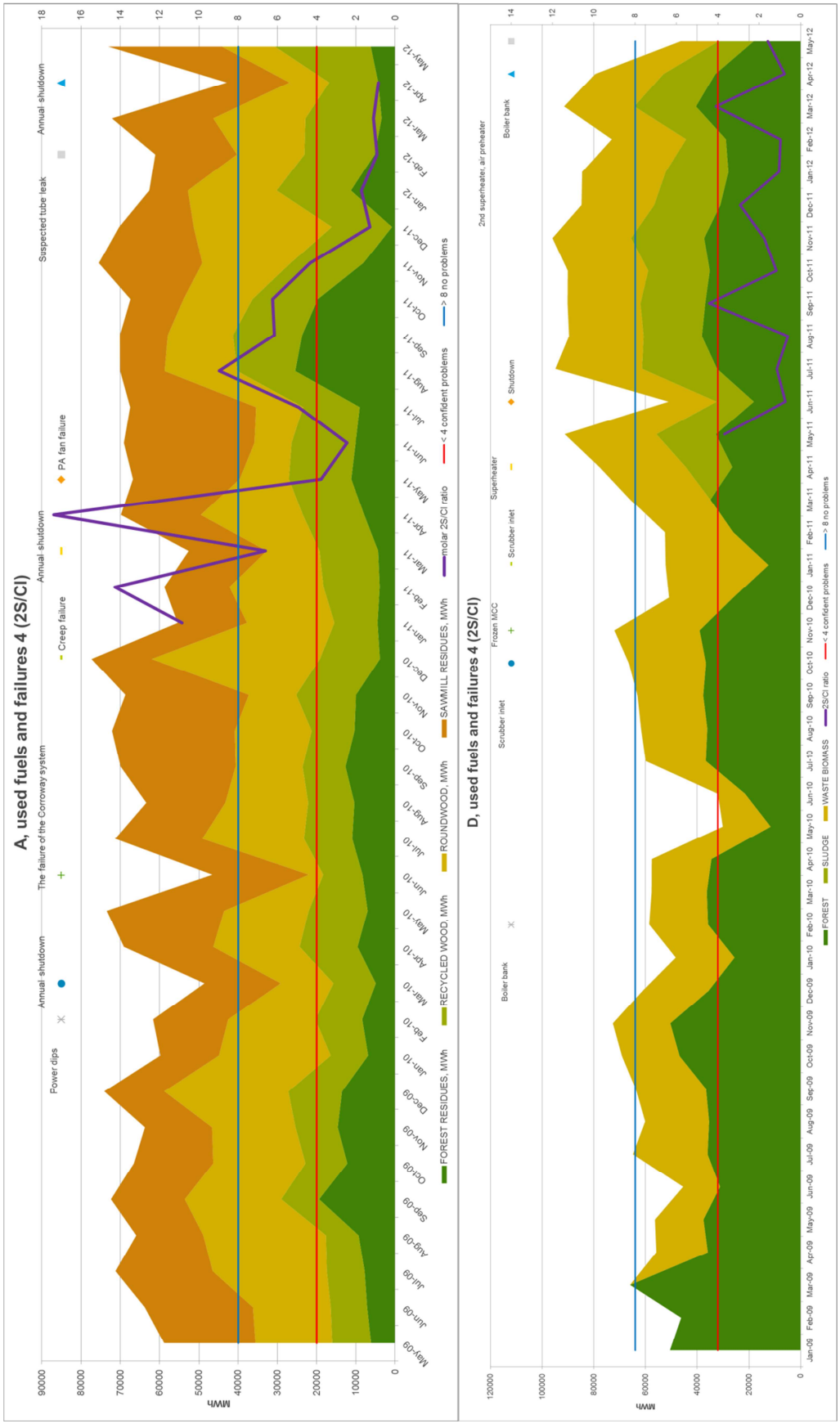
APPENDIX 2: USED FUELS AND THE ASH CONTENT OF THE WHOLE MIXTURE FOR POWER PLANTS A AND D



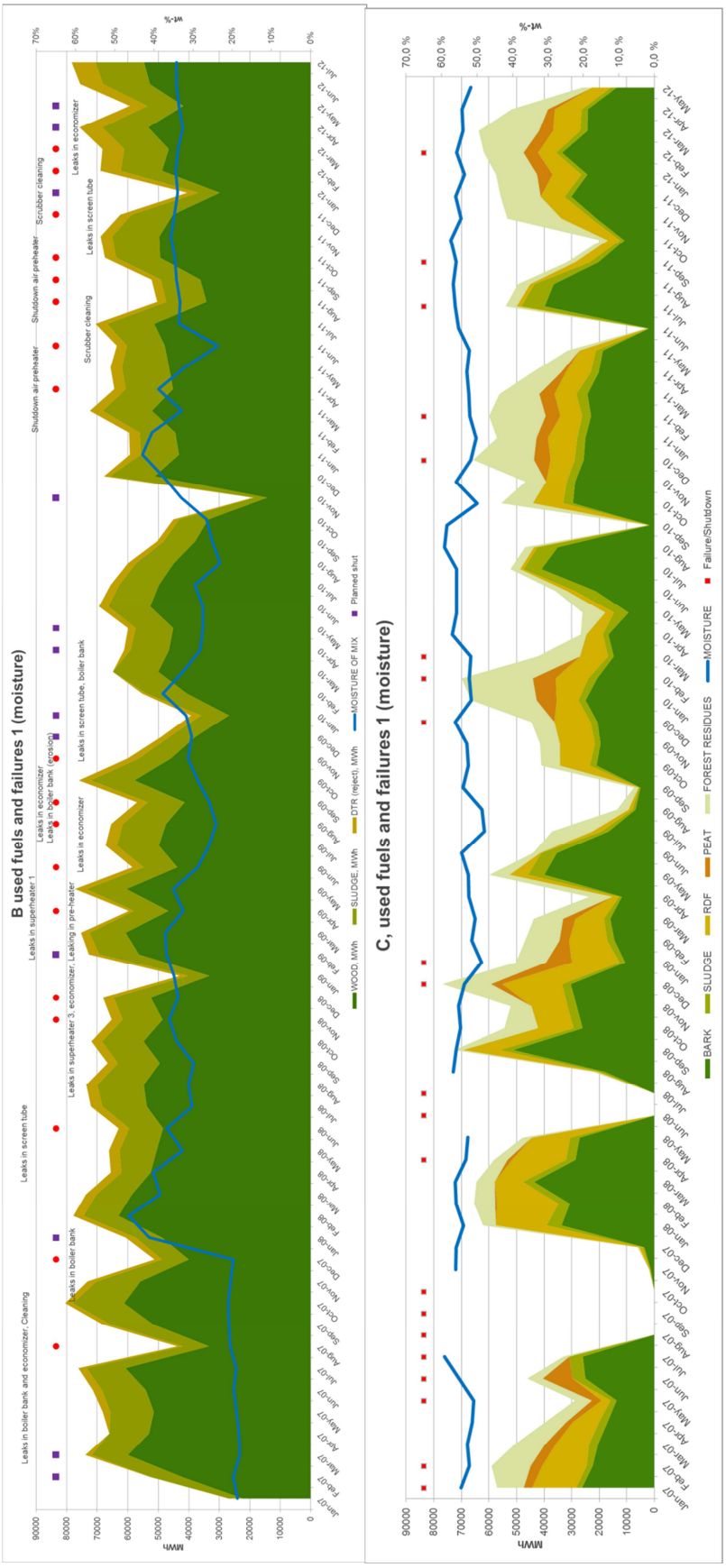
APPENDIX 3: USED FUELS AND THE CHLORINE CONTENT OF THE WHOLE MIXTURE FOR POWER PLANTS A AND D



APPENDIX 4: USED FUELS AND THE MOLAR 2S/CL RATIO OF THE WHOLE MIXTURE FOR POWER PLANTS A AND D



APPENDIX 5: USED FUELS AND THE MOISTURE CONTENT OF THE WHOLE MIXTURE FOR POWER PLANTS B AND C



C	Failure/Shutdown
Jan-07	Boiler trip, impulse line outside
Feb-07	Boiler trip, failure on the national grid
May-07	Boiler trip, too fast lead ingrease
Jun-07	Boiler trip
Jul-07	Boiler trip
Aug-07	Yearly maintenance
Sep-07	Yearly maintenance
Oct-07	Yearly maintenance
Apr-08	Boiler trip, HIMA logic card failure
Jun-08	Planned standstill
Jul-08	Planned standstill
Sep-08	Yearly maintenance
Dec-08	Boiler trip, O2 measurement failure
Jan-09	Shutdown, bed material change
Apr-09	Planned standstill
Jun-09	Planned standstill
Sep-09	Yearly maintenance
Dec-09	3 pcs. Trips, '- freesing of pressure impulse line, -disturbance of CFB boiler, - 6 kV short circuit
Feb-10	Boiler trip, drum level
Mar-10	Boiler trip, flue gas fan stopped
Jun-10	Planned standstill
Sep-10	Yearly maintenance
Dec-10	Boiler trip, gas pressure after bagfilter too high
Feb-11	Boiler trip, operational failure
Jun-11	Planned standstill
Jul-11	Boiler trip, primary air fan stopped
Sep-11	Boiler trip, operational failure, yearly maintenance
Feb-12	Boiler trip, rapid change of fuel quality